

AN EXPERIMENTAL STUDY ON GEOTEXTILE-SOIL FILTER SYSTEM

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ABSTRACT

AN EXPERIMENTAL STUDY ON GEOTEXTILE-SOIL FILTER SYSTEM

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Filters have been used in earth structures such as retaining walls, earth dams etc. to prevent the loss of particles induced by seepage of water. Traditionally granular filter materials are used, however, they are becoming more difficult to obtain and transport to the construction site and transportation of granular material raise the cost of construction and carbon footprint of the project. Therefore, the need for an alternative filter material arises, and geotextiles can be considered as one of the best options.

The experimental investigation was conducted in the laboratory to evaluate the Gradient Ratio test method for steady unidirectional flow through non-woven geotextiles. Tests were performed according to specification of ASTM D5101. Kayseri Clay that is a sample dam clay according to specification of State Hydraulic Works (DSI) was used as a base soil to reflect the actual clay core earth fill dam behavior, and two non-woven geotextiles, having different opening area and thickness, were used. Also, the granular filter-clay combination was tested to compare geotextile filter and granular filter filtration behavior.

It has been found that the stabilization in the permeability of system was greatest and fastest for the geotextile that had smaller opening area, and amount of loss of fines was detected in the case of having larger opening size and thinner geotextile system.

Furthermore, using two-layers of geotextile in the system showed better filtration performance.

The filtration performance of the geotextile was affected by the compaction state of the base soil. The denser compaction of clay positively affected the filtration performance.

Finally, the system was analyzed in three zones of permeameter. It is observed that the system permeability behavior was very similar to permeability of soil layer next to geotextile. The results of this study are believed to help further understand the use of non-woven geotextiles in earth dams as filter material.

Keywords: filter, granular, non-woven geotextile, earth dam

ÖZ

GEOTEKSTİL-ZEMİN FİLTRE SİSTEMİ İÇİN DENEYSEL BİR ÇALIŞMA

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Filtreler istinat duvarları, dolgu barajlar gibi yapılarda su sızıntısının neden olduğu partikül kaybını önlemek için kullanılır. Genellikle barajlarda granüler filtre malzemeleri kullanılmaktadır. Ancak, bu filtre malzemesinin elde edilme ve şantiyeye taşınma işlemleri projenin maliyetini arttırmaktadır. Bu süreçle birlikte projenin karbon ayak izi de artmaktadır. Bu nedenle, alternatif bir filtre malzemesine ihtiyaç duyulmakta olup geotekstiller bu ihtiyaç için en iyi seçeneklerden biri olarak düşünülebilir.

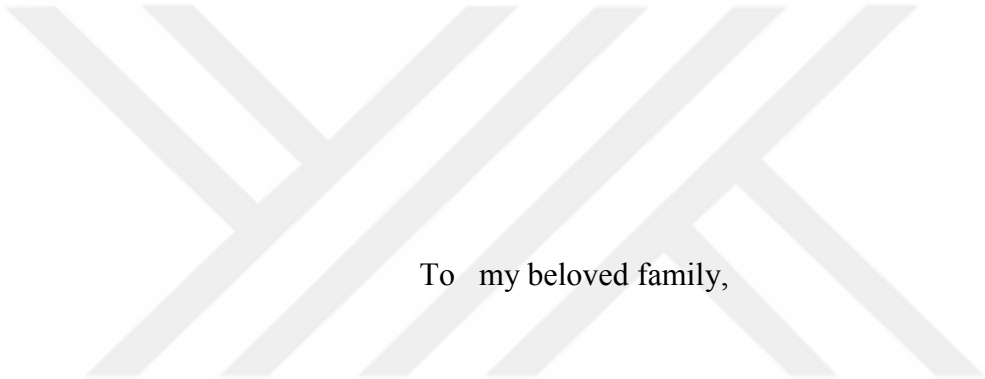
ASTM D5101 standardına göre, örgüsüz geotekstillerin sabit tek yönlü akış altındaki gradyan oranı değişimi laboratuvar deneyler ile analiz edilmiştir. Gerçek kil çekirdekli toprak dolgu baraj davranışını yansıtmak için devlet su işleri teknik şartnamesine göre örnek bir baraj kili olan Kayseri kili kullanılmıştır. Filtre malzemesi olarak ise farklı göz açıklık ve kalınlığa sahip iki tip örgüsüz geotekstil kullanılmıştır. Ayrıca, granül filtre-kil kombinasyonu da test edilmiş olup geotekstil filtre ile karşılaştırılmıştır.

Elde edilen sonuçlara göre, küçük göz açıklığına sahip geotekstil sistemlerinde, sistem geçirgenliğinin sabit değere ulaşması en hızlı şekilde gerçekleştiği

gözlemlenmiştir. İki kat geotekstil kullanılarak yapılan deneylerde filtrasyonun daha iyi gerçekleştiği analiz edilmiştir.

Kilin daha yoğun sıklıkta hazırlanması filtrasyon performansını olumlu yönde etkilemiştir. Deney sisteminde kilin bulunduğu hücre üç bölgede incelenmiştir ve sistem geçirgenliğinin geotekstilin yanında bulunan zemin tabakasının geçirgenliği ile çok benzer olduğu görüşmüştür. Bu çalışmadan elde edilen sonuçlar ile örgüsüz geotekstillerin toprak barajlarda filtre malzemesi olarak kullanımının daha iyi anlaşılmasına yardımcı olduğuna inanılmaktadır.

Anahtar Kelimeler: filtre, granüler, örgüsüz geotekstil, dolgu baraj



To my beloved family,

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LIST OF ABBREVIATIONS AND SYMBOLS

AOS	Apparent opening size of geotextile
POA	Percentage opening area in woven geotextile
COS	Characteristic opening size
GSD	Soil grain size distribution
C_c	Coefficient of Curvature
C_u	Uniformity coefficient ($\frac{D_{60}}{D_{10}}$)
C'_u	Linear coefficient of uniformity [$C'_u = \frac{d'_{60}}{d'_{10}} = \sqrt{\frac{d'_{100}}{d'_0}}$]
D_x	Diameter of soil grain at x % in cumulative
d_x	Particle size such that the soil contains x% by mass of particles smaller than d_x
d'_x	Linear particle size such that the soil contains x% by mass of particles smaller than d'_x
O_x	Openin size (inscribed diameter) at x % in cumulative geotextile opening size distribution
O_F	Geotextile apparent opening size
GR	Gradient ratio
K_R	Permeability ratio
k_{system}	System permeability
k_{soil}	Soil permeability
k_F	Hydraulic conductivity of filter
k_S	Hydraulic conductivity of soil
i	Hydraulic gradient
i_S	Hydraulic gradient in the soil next to the filter
i_{mn}	Hydraulic gradient measured between the Port m and Port n
n	Porosity
n_{GT}	Geotextile porosity
A_R	Relative open area (open area / total area)
$N_{constrictions}$	Number of constrictions of geotextile
t_G	Thickness of geotextile
ρ	Soil specific density
ρ_F	Fiber density
I_D	Relative density of soil
μ_{GT}	Mass per unit area of the geotextile

d_f	Fiber diameter
μ_T	Water viscosity at temperature of the test
μ_{20}	Water viscosity at 20 °C
V	Volume of the measured flow
V_F	Velocity of water passing through the filter
k_T	Permeability at temperature of the test
h_m	Water head on manometer m
l_{n-m}	Thickness of the soil between manometers n and m



CHAPTER 1

INTRODUCTION

1.1 General Information

Filtration is one of the most important issues in the design of dams and levees. Design of a filter requires two main criteria to be satisfied: permeability and retention. Filter should provide free flow of water (it should be permeable enough), and filter should not allow the fine particles to be carried through the filter (it should have sufficiently small openings not to allow particles to pass). The movement of fine particles through dam body can result in serious consequences such as piping, even failure of a dam, if it is not controlled properly. According to FEMA (2011), approximately 50% the dam failures are caused due to excess seepage. Movement of soil and loss of the soil from dam body (piping) leads to greater seepage, so it leads to more soil erosion. In this context, selection of proper filters plays a key role.

Traditionally granular filters, which are composed of natural / crushed aggregates obtained from quarries, are used in earth dams. As stated by UNEP GEAS (2014) it is getting more difficult to find clean granular material from nature and that mining them from quarries negatively affects the environment. Beside the granular filters, geotextiles would be one of the best options for filtration purpose in many parts of dams such as chimney drains, trench drains, blanket drains and heel drains. The use of geotextile filters is preferred in particular for the protection of the environment and natural resources, sustainability, reducing the carbon footprint of the project and and may reduce the cost.

In this study, performance of geotextile to be used as a filter material next to a clay-core of an earth dam is investigated by conducting laboratory tests. Filtration performance of geotextile-soil system is analyzed under different hydraulic

gradients in accordance with the specification of ASTM D5101. Behavior of two geotextiles having different apparent opening size, thickness and mass per unit area is investigated and compared during these filtration tests. Also, a comparative evaluation of the filter criteria in the international standards for granular filter and geotextile filter is carried out for suggesting a proper design method of a geotextile filter.

1.2 Problem Statement

For the earth fill dams, generally, granular soil is used as a filter material. However, in recent years there are some difficulties in finding proper granular material in Turkey, as well as around the world. They are becoming more difficult to obtain and transport to the construction site and transportation of granular material raises the cost of construction and carbon footprint of the project. Furthermore, production of clean granular materials from rock quarries causes disturbance of the natural resources. Therefore, use of geotextiles as a filter material is being considered instead of granular soil.

Researchers have defined the geotextile design criteria based on retention and permeability properties (Giroud 1982, Lawson 1986, Christopher and Holtz 1989, Lafleuer et al. 1989, Luetlich et al 1992, Giroud 1996). There are many studies about the filtration behavior of soil-geotextile system using ASTM D5101 gradient ratio test. Some of them conducted the tests on slurry sand (Aydilek & Edil, 2003; Palmeira, Gardoni, & Bessa da Luz, 2005; Wu, Hong, Yan, & Chang, 2006; Weggel & Dortch, 2012; Miszkowska, Lenart, & Koda, 2017), and some of the researchers have analyzed the filtration performance on sludge clayey type soil (Eams, 1999; Kutay & Aydilek, 2005; Gapak, Yamsani, Sreedeeep, & Rakesh, 2017; Stoltz, Delmas, & Barral, 2019a). Also, some experimental studies are conducted on fly ash or dredged sediments (Kutay & Aydilek, 2005; Muthukumaran & Ilamparuthi, 2006). However, there is a lack of information about the filtration performance of compacted clay soil-geotextile system. Defining how the design criteria of geotextile affects the results for the case of compacted clay

soil-geotextile system is the key to understand the mechanism and can change how we approach to the specific problems such as design of earth dams.

1.3 Research Objectives

The main goal of this study in general is to investigate and demonstrate the possibility of using geotextile filters instead of granular filters next to where clay is used as a base material, such as in the clay-core of an earth dam. Some of the objectives are:

- 1) Reviewing the existing methodology of geotextile design criteria for filtration.
- 2) Experimentally demonstrating feasibility of non-woven geotextile used as a filter material, by performing a series of gradient ratio tests on soil-geotextile system for compacted clay.
- 3) Analyzing the compatibility of the soil and non-woven geotextile system in terms of permeability, gradient ratio and flow rate with time. Interpretation of data and evaluating the existing design criteria in terms of applicability for such clay under compaction. Also, developing a better understanding for the effects of thickness, apparent opening size, and mass per unit area of geotextile material on filtration mechanism by changing these properties during test series.
- 4) Identifying any problems in selection of non-woven geotextile according to design criteria in terms of allowing the flow of water (permeability), retain the solid particles and survivability during and after installation.

The results of this study are believed to help to further understanding of the use of non-woven geotextile in earth dams as a filter material.

1.4 Scope

The thesis consists of four chapters. In Chapter 1, the topic and the objectives of the research are presented. In Chapter 2, a literature review is provided. In Chapter 3, the experimental study is described such as the test set-up, the used materials, the sample preparation and the test procedure. Also, all results and interpretation of them are provided. Lastly in Chapter 4, the outcomes of the study are summarized and the topics for further studies are drawn as suggestions.



CHAPTER 2

LITERATURE REVIEW

2.1 Definition and Types of Geotextiles

“Geotextile” term was used for the first time by Giroud in 1985. Before, they were called by various names, e.g., filter fabrics, synthetic fabrics, road rugs, construction cloth, filtration material, etc. (Koerner, 2016).

Geotextile is one of the major types of geosynthetics family. They have been used for various purposes in construction projects, such as separation, drainage, filtration, reinforcement and erosion control. Filtration function is one of the key properties of geotextiles among all applications and they are widely used for this purpose in geotechnical engineering.

Geotextiles are typically made from polypropylene and polyester. They are mainly classified according to production procedure. The variation of properties comes from having numerous types of fibers used and geotextile manufacturing processes. The most common types of geotextiles are nonwoven and woven geotextiles (Figure 2.1).

Woven geotextiles are made up with yarns with one or several fibers positioned in perpendicular and regular pattern. They are very compact and can have high tensile strength due to their production process, and also their strength changes with direction of fibers and weaving technique. Woven geotextiles are generally used for separation and reinforcement in geotechnical engineering by using their strength coming from manufacturing process.

Similarly, nonwoven geotextiles are made up with fibers or yarns, but in this case, they are arranged in a random pattern, and in a planar structure. They are manufactured by needle punching, spun bonding, or resin bonding. The bonding of

the fibers can be produced using various mechanical, heat or chemical-based processes.

The type of manufacturing process depends on the required properties and purpose of usage for the end products. By the variety in production process, nonwoven geotextiles can have large range in thickness and weight, which are needed and very important properties for drainage, filtration and protection applications.

Nonwoven geotextiles are mostly used based on their filtration function. Since the fibers of nonwoven geotextile are oriented in random pattern, they are capable of retaining the soil particles without clogging. Figure 2.1 shows the pattern of yarns in woven and nonwoven geotextiles.

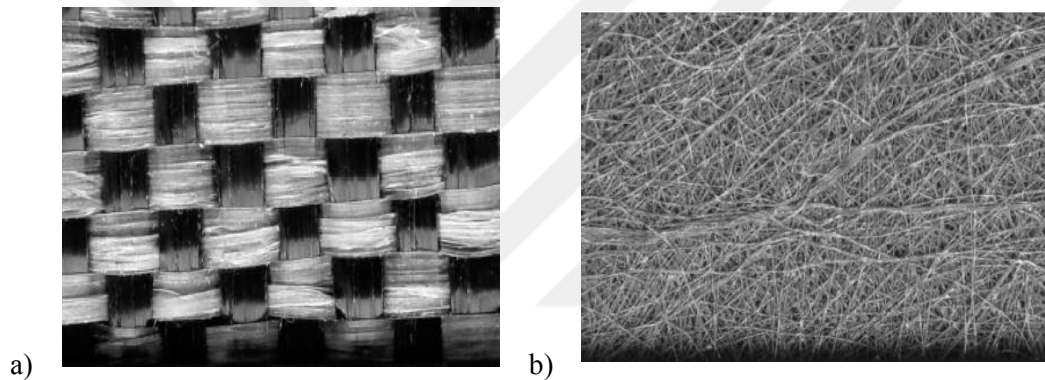


Figure 2.1 a) Woven slit film geotextile, and b) Nonwoven heat-bonded continuous filament geotextile (FHWA, 2008)

2.2 Properties of Geotextiles

2.2.1 Physical Properties

The physical properties of geotextiles mainly depend on the raw material and manufacturing type and processes used. Specific gravity, mass per unit area, apparent opening size (AOS) and thickness can be considered as some of the fundamental physical properties of geotextiles. Tests conducted for determining the physical properties of geotextiles are called as index tests (Torosian & MacMillan, 2016).

- Specific gravity is defined by ASTM D4439 (Fibers, 2009) as the ratio of the density of geotextile to the density of a reference material in a unit volume. Actually, the specific gravity property of a geotextile comes from the specific gravity of raw material. The raw materials of geotextile, polyethylene and polypropylene, have specific gravities in the range of 0.9-0.96 (Koerner, 2012).
- The mass per unit area is a property that can affect directly the other geotextile properties, such as tensile strength, tear strength and apparent opening size. For example, as mass per unit area increases, the tensile strength and puncture resistance will also increase. The mass per unit area of geotextile is measured according to ASTM D5261.
- Thickness is defined as the distance between the top and bottom of a geotextile under a specified pressure of 2 kPa. The thickness affects the other geotextile properties, such as tensile strength and tear strength. Thickness of geotextile is measured according to ASTM D5199 (ASTM, 2019).

2.2.2 Mechanical Properties

The geotextile should be selected in accordance of both their function and durability of them in construction area. In other words, the ability of a geotextile to survive under stresses during installation or life time of construction is very important property (Zanzinger, 2016).

American Association of State Highway and Transportation Officials (AASHTO) provides a table for minimum required properties of geotextiles for installation survivability (Table 2.1). Three different degrees of installation survivability stresses are defined as Class 1, 2 and 3. In Class 1 there is significant potential for damage to geotextile (i.e. severe or harsh site survivability conditions, such as not very careful handling of geotextiles, careless/negligent site activities, tires of vehicles, sharp aggregates, sharp objects may come in contact with the geotextile which might cause damage etc.), Class 2 is typical conditions (which can be

considered as the default condition in the absence of any other data) and Class 3 represents mild conditions where there is little or no damage potential to geotextile. The minimum requirements for permittivity, AOS and Ultraviolet stability are different based on geotextile application. So, subsurface filtration minimum requirements are presented in Table 2.1.

Table 2.1 AASHTO geotextile minimum strength requirements for different construction site survivability conditions (modified from Koerner, 2012)

Property	Test Methods	Geotextile Classification					
		Class 1		Class 2		Class 3	
Elongation		< 50% woven	≥ 50% nonwoven	< 50% woven	≥ 50% nonwoven	< 50% woven	≥ 50% nonwoven
Grab Strength, N	ASTM D4632	1400	900	1100	700	800	500
Sewn Seam Strength, N	ASTM D4632	1260	810	990	630	720	450
Tear Strength, N	ASTM D4533	500	350	400	250	300	180
Puncture Strength, N	ASTM D4833	500	350	400	250	300	180
		Percent In-Situ Soil Passing 0.075 mm					
		< 15		15 to 50		>50	
Permittivity, sec ⁻¹	ASTM D4491	0.5		0.2		0.1	
Apparent Opening Size, mm	ASTM D4751	0.43 maximum average roll value		0.25 maximum average roll value		0.2 maximum average roll value	
Ultraviolet Stability, %	ASTM D4355	50% after 500 hours exposure					

2.2.3 Hydraulic Properties

Hydraulic properties are important for geotextiles if they are used in the function of filtration. The hydraulic requirements for filtration purposes are retention, clogging and hydraulic conductivity.

- The opening size of geotextile is a fundamental property in the choice of a geotextile as a filter material. The geotextile opening size and pore size distribution can be determined by ASTM D4751 dry sieving method and EN ISO 12956 wet sieving method (Cazzuffi, Mandaglio, & Moraci, 2016). The opening size and pore size distribution properties of geotextiles are important factors for retention criterion in the design and selection stage for filtration.
- The porosity is defined as the ratio of the volume of void to the total volume. Porosity is directly related with the permeability of geotextile. Therefore, porosity is one of the most important properties for non-woven geotextiles to have proper filtration performance. For the geotextile, the porosity can be calculated indirectly as in Equation 2.1 (Cazzuffi et al., 2016);

$$n_{GT} = 1 - \frac{m}{\rho_F t_G} \quad (2.1)$$

where: n_{GT} is the geotextile porosity in percentage, m is the mass per unit area in g/m^2 , ρ_F is the fiber density in g/m^3 and t_G is the thickness of the geotextile in meter.

- Permittivity is the parameter that represents the water flow capacity of geotextile in the cross-plane direction. Permittivity can be defined as the ratio of cross-plane permeability for water flow to the thickness of the geotextile. It can be measured by experimental method according to ASTM D4491 and ISO 11058.

2.3 Filtration Mechanism of Geotextile

Any material that is used for filtration function in geotechnical engineering must have the ability of passing water through it, and maintain the stability of the soil structure by preventing loss of soil with migration (Ahmet H. Aydilek, 1991).

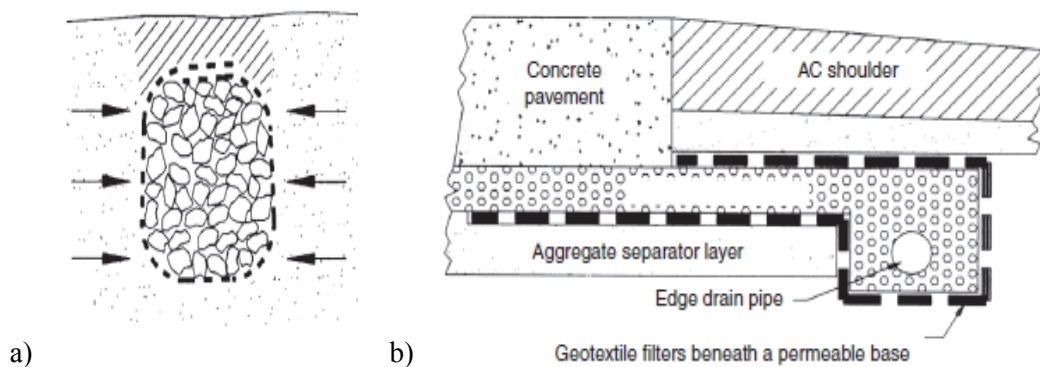


Figure 2.2 a) Geotextile filter around trench drains and edge drains, and b) Geotextile filters beneath a permeable base (Holtz, Christopher, & Berg, 1998)

In recent years, geotextiles are widely used as a filter material in many geotechnical applications (Figure 2.2). By comparing their performance in accordance not only about filtration but also in economy, ease of placement and sustainability of them, geotextile filters are getting more popularity in geotechnical applications.

Filtration actually develops by rearranging the base soil. When water passes through filter, some particles of soil are carried toward the filter and drain. By movement of soil particles, they are relocated in accordance to their sizes, and this leads to change in grain size distribution, porosity and permeability within both base soil and filter material. First the larger diameter-particles are placed next to filter material, then little bit smaller ones are moved towards filter and so on. This rearrangement in base soil next to filter produces a filter zone, which is also called as "filter cake/bridge" or "bridging network" (Watson & John, 1999; Aydilek, 2006). The form of filter cake in the soil-geotextile system is shown schematically in Figure 2.3.

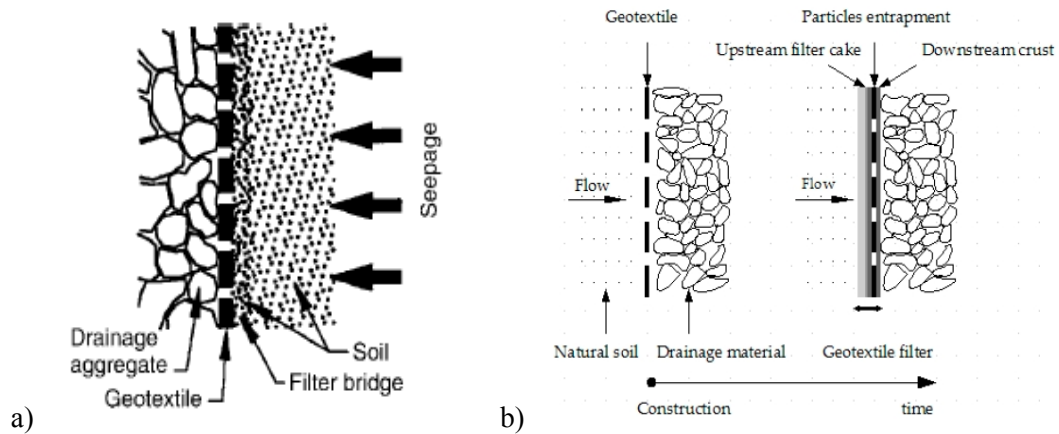


Figure 2.3 a) Soil retention by means of bridging zone (Holtz et al., 1998),
b) Evolution of geotextile filter structure over time (Miskowska, Lenart, & Koda, 2017)

Once this filter cake is established, it allows the seepage to continue with trapping the smallest soil grains. The filter cake formation can be considered as equilibrium in soil-geotextile system. If the system reaches equilibrium in terms of filtration process by forming bridging network, there might be no doubt about the filtration process for the service life of the geotextile material. According to Koerner and Ko. (cited by Aydilek, 2006), the time needed for the occurrence of filtration cake on upstream of geotextile filter varies between 24 and 1000 hours. Observed filtration behavior as a consequence of filter cake is a function of the geotextile apparent opening size (O_F), porosity and density of the geotextile, and the properties and gradation of the base soil.

To form filter cake in the system, the characteristic pore size opening of the geotextile has very important role to provide compatibility of retention and permeability. Similarly, for the granular filter material, the basic design approach is matching the geotextile apparent opening size (O_F) to characteristic particle size of the soil (D_x). The pore size distribution critically effects the filtration mechanism. The selection criteria of characteristic opening size of geotextile will be detailed in Chapter 3.

If the pores are too large, soil particles can pass thorough the pores easily and soil piping will occur in the system. Soil piping can occur into internal erosion that involves loss of soil particles with a range of sizes (Ergeneman, 2001).

On the other hand, if the pores are too small soil particles will start to accumulate with time passing and blocking (or plugging), blinding or clogging may develop.

- Blocking is another situation that develops due to having too small opening size of geotextile. In this case, the coarse particles that directly contact with the geotextile surface plug up the filter openings, and those particles prevent the fine particles and also fluid to pass.
- Blinding will occur when fine particles migrate and accumulate in the interface zone close to the geotextile, and this leads to decreasing porosity in the interface zone. Then, hydraulic conductivity increases locally in the fine particles accumulated zone, but decreases in the interface zone with the geotextile. Therefore, the system cannot satisfy the equilibrium in terms of hydraulic conductivity and average permeability may decrease with time passing (Lee, 2006).
- Clogging will occur when migrating the fine particles penetrate into the filter fabric because of too narrow pore openings of geotextiles. Fine particles can be accumulated on the upstream face of geotextile and they prevent its drainage channels to function. Thick non-woven geotextiles have greater risk of clogging (Koerner, 1994).

The piping, bridging and blinding are conceptually represented in Figure 2.4.

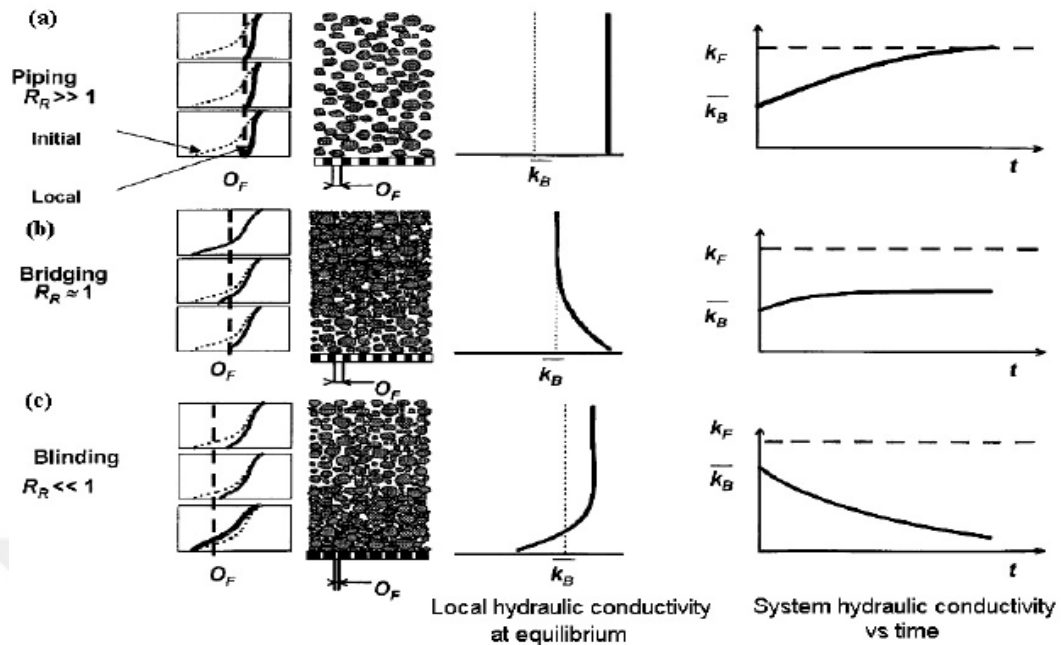


Figure 2.4 Piping(a), bridging(b) and blinding(c) mechanisms associated with different geotextile opening size and soil behaviors (J. Lafleur, 1999)

In Figure 2.4;

Left hand side: Soil grain size distribution (GSD) and its variation in the vicinity of the geotextile (dotted curve: initial GSD; plain curve: final GSD; $R_R = O_F/d_i$; O_F : filter opening size; d_i : indicative particle size of protected soil)

Center-left: Schematics of resulting granular structure

Center-right: Profile of resulting soil hydraulic conductivity in function of distance to geotextile (k_B : initial soil hydraulic conductivity (dotted line))

Right-hand side: Evolution of system average hydraulic conductivity in function of time, as compared to k_F (virgin hydraulic conductivity of geotextile).

The internal erosion and clogging situations are also illustrated in Figure 2.5.

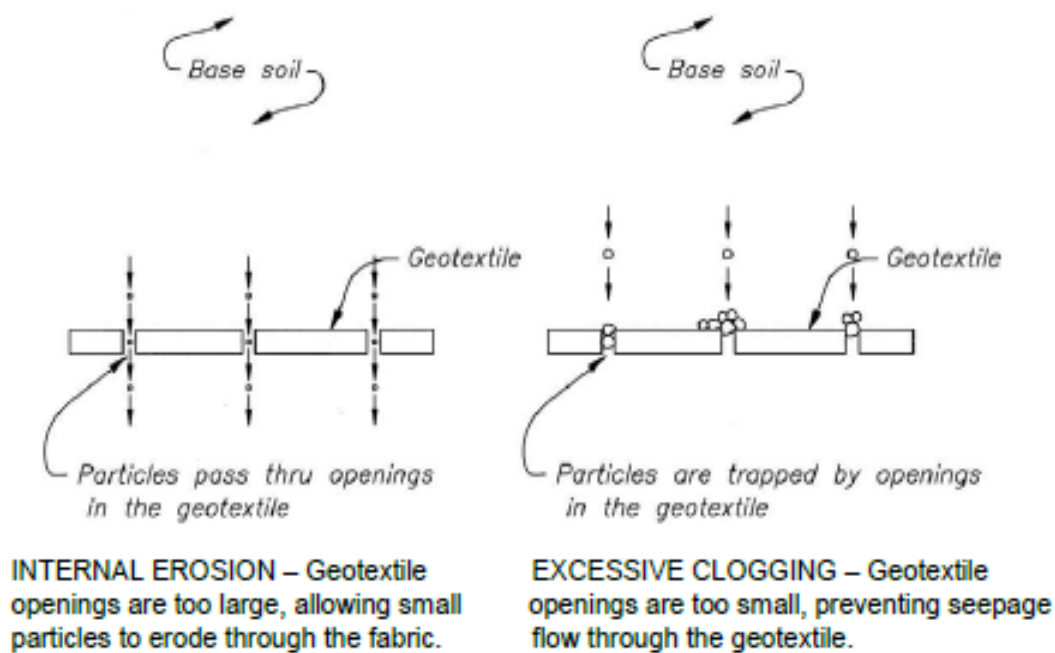


Figure 2.5 Illustration of a geotextile filter in the case of soil internal erosion and excessive clogging (U.S. Department of the Interior, 2015)

For all cases, a permeable "filter cake" fails to form. So, the geotextile is not suitable as a filter for the system.

Besides the opening size of the geotextile, porosity, density and thickness of the geotextile are very important factors for filtration process, and also for occurrence of filter cake. Their importance and selection criteria will be explained in Chapter 3 as well.

On the other hand, the base soil has also very important role on forming filter cake as well as the used geotextile. According to Luettich et al. (1992), the application field should be analyzed and the properties of the soil that is adjacent to the filter should be clearly indicated. Void ratio, grain size distribution, pore volume of the soil, even the shape of the particles (sharp contact points) have important roles on the filtration mechanism. Since the filter cake is a soil media that is developed by accumulation of base soil in accordance its grain size, the base soil should be well graded.

2.4 Recent Studies

The use of geotextiles as filter materials in geotechnical engineering has gained more experience during the past four decades. There is significant amount of research on the use of geotextile as a filter material (Giroud 1982, Lawson 1986, Christopher and Holtz 1989, Lafleuer et al 1989, Luettich et al 1992, Giroud 1996), and those researches define design criteria based on retention and permeability properties of geotextiles. Some of the design criteria are explained in following parts of the thesis.

Aydilek and Edil (2003) conducted an experimental study on wastewater treatment sludge and six different types of nonwoven geotextiles. They used the gradient ratio test (ASTM D5101) and permittivity test (ASTM 4491) to analyze the filtration behavior of sludge-nonwoven geotextile system in the long term condition. They state that permittivity of used geotextile is the most important parameter related with its filtration performance. They observed less clogging and more piping with increasing permittivity.

Palmeira et. al. (2005) presents their studies on gradient ratio test under normal stresses using different types of soil-geotextile systems. The results show that, permeability of geotextile is always greater than the permeability of base soil for tested systems even under normal stresses of 2000 kPa. This also shows that the applicability of the current permeability criteria for the test systems is conservative.

Kutay and Aydilek (2005) have conducted an experimental study on fly ash and dredged sediments with woven/nonwoven geotextile combinations. They used the gradient ratio test (ASTM D5101), and the results show that use of two-layer woven/nonwoven geotextile significantly increases filtration performance of the system rather than a single woven geotextile. Moreover, the dredged sediments cause more clogging potential than fly ash because of its cohesive nature and its relatively higher fines content.

In another research done by Stoltz, Delmas and Barral (2019), the clayey sludge and various types of geotextiles are used for testing to define how geotextile

characteristics affect the filtration capacity of geotextile. The findings show that geotextiles with the smallest opening size (opening size smaller than 0.06 mm) give better results in terms of filtration for the clayey sludge. Also, the thermally bonded nonwoven geotextile shows better performance than the needle punched one.

Mittal and Anamika have conducted an experimental study with construction of a small scaled earth dam in the laboratory. They used granular material and geotextile as a filter material to compare their filtration performance. In this research, flow direction is in vertical as in the site for the earth dam. Results show that the seepage rate through the dam model cross-section is very close for both granular filter and geotextile, and they stated geotextile can be used at site as a filter material.

2.5 Granular Material Filter Criteria

When using granular material as a filter, Terzaghi's filter criteria is used, which addresses two main properties of filter material, which are permeability and retention criteria.

The classical Terzaghi's criteria for granular filters are expressed as follows:

$$d_{15F} \geq (4 \text{ or } 5) \cdot d_{15S} \quad (2.2)$$

$$d_{15F} \leq (4 \text{ or } 5) \cdot d_{85S} \quad (2.3)$$

where d_x is the particle size such that the soil contains x% by mass of particles smaller than d_x . $d_{15F} = d_{15}$ of the filter; $d_{15S} = d_{15}$ of the soil; and $d_{85S} = d_{85}$ of the soil.

The Equation 2.2 is directly related with the permeability criteria of the granular filter. It states that the d_{15} of the filter must not be too small. On the other hand, the Equation 2.3 means that the d_{15} of the filter must not be too large, which is for the retention criterion for the filter.

Based on granular filter criteria, the criteria for geotextiles have been defined. The selection criteria for geotextile will be explained in Section 2.7.

2.6 Geotextile Filter Criteria

For geotextiles to perform properly as filters, the material should have openings large enough to allow free flow of water (permeability criterion), and small enough to retain all particles that are likely to migrate (retention criterion). Therefore, a compatibility should be achieved between these two basic requirements, which are retention of soil and cross-plane permeability of water.

Beside the principle requirements for geotextile used as a filter material, there is also a requirement such that having adequate strength to ensure that the geotextile is not damaged during the installation and the service life of structure. ICOLD Bulletin 55 (1986) of “Geotextiles as Filters and Transitions in Fill Dams” can be considered as the oldest specification regarding the use of geotextile in dams as a filter material. ICOLD (1986) specifies some filter criterions for geotextiles. For example, in the document the value of permittivity is recommended to select 100 times the base materials permittivity to be on the safe side. After that years, use of geotextile filters in dams has gained popularity.

Many studies on the use of geotextile in dams as the filter material have been made and stated in various international specifications and documents. Some of the studies will be detailed in Section 2.7.1, 2.7.2 and 2.7.3.

2.6.1 Filter Criteria of Geotextile According to Giroud (2010)

Giroud (2010) developed four criterion for geotextile to use as a filter, which are criterion for permeability, criterion for retention, criterion for porosity and thickness.

Based on the main points of filtration, which are permeability of any liquid or gas and retention of soil, first two design criteria for all type of filters have been

determined. However, according to Giroud (2010) the design and usage criteria of geotextiles as a filter material cannot be limited only with permeability and retention criteria. To perform properly as filter, two additional criterion are needed for geotextile; one of them is sufficient number of opening (porosity) and the other is sufficient filter thickness.

The filter criteria defined by Giroud (2010) is applicable only for cohesionless base soil and optimum retention case. The optimum retention is defined as the case of the filter should retain soil as a whole but not necessarily all particles. This type of filters is used for drainage trenches, and blanket drain in dams. The four criterions developed by Giroud will be explained in this part of the Chapter 2.

1. Permeability Criteria

According to Giroud (2010), the permeability criterion needs two requirements; one of them is the pore pressure and the other one is the flow rate. For the pore pressure requirement, the following condition, showing in Equation 2.4, should be met properly.

$$k_F \geq i_S k_S \quad (2.4)$$

where: k_F is the hydraulic conductivity of filter, k_S is the hydraulic conductivity of soil, and i_S is the hydraulic gradient in the soil next to the filter.

On the other hand, for the flow rate requirements the necessary condition that should be achieved for conductivity is expressed in Equation 2.5.

$$k_F \geq k_S \quad (2.5)$$

Based on these two requirements, Giroud (2010) suggests that for the permeability criteria of filter maximum of $i_S k_S$ or k_S should be selected. Typical values of the hydraulic gradient in soil next to filters have been shown in Table 2.2.

Table 2.2 Typical values of the hydraulic gradient in soil next to filters (Giroud, 2010)

Applications	Hydraulic Gradient
Dewatering trench	≤ 1.0
Vertical wall drainage	1.5
Road edge drain	≤ 1.0
Inland waterway protection	≤ 1.0
Landfill drainage layer	1.5
Dam toe drain	2.0
Drain behind dam clay core	3 to > 10
Liquid reservoir with clay liner	> 10

2. Retention Criteria

According to Giroud (2010), retention mechanism for the granular filter basically depends on internal stability of retained the soil. Internal stability of a soil depends on many parameters. A soil can be internally stable if the soil has coefficient of uniformity less than three (Giroud, 2005). If the soil has sufficient particle size distribution to form continuous skeleton individually, then this skeleton retains the particles that are a little smaller, and this retained part also entraps a little small particles and so on. With this procedure in the soil, a zone will be developing, which is named as filter cake.

Actually, the filter performance of granular materials starts after filter cake region develops in the structure. Based on this fact, the filtration performance of geotextile can be obtained with the same conditions as in granular filters. The base soil's stability properties depend on the coefficient of uniformity and density, and this is valid only for soil having grain size distribution curve that is not gap-graded. In filtration case with geotextile, the opening size of filter (O_F) has important role on retention criteria and also for obtaining filter cake zone.

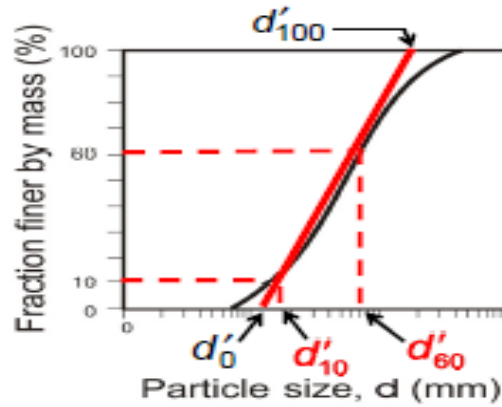


Figure 2.6 Representation of linear coefficient of uniformity (Giroud, 2010)

In Giroud (2010) study, a linear coefficient of uniformity is defined to determine the filter opening size. It is represented in Figure 2.6. The linear coefficient of uniformity is calculated from the straight line that closely follows the central part of the grain size distribution curve, and by extrapolating the middle straight line portion backward and forward to obtain the values of grain sizes corresponding to 0% and 100% passing. It is calculated as in Equation 2.6.

$$C'_u = \frac{d'_{60}}{d'_{10}} = \sqrt{\frac{d'_{100}}{d'_0}} \quad (2.6)$$

Where d'_x is the 'linear particle size' derived from the straight line in Figure 2.6. The subscript x in d'_x is defined after Equation 2.2.

In addition to the linear coefficient of uniformity, the density state of the base soil is also important to determination of filter opening in geotextile. The internal stability of soil depends both its coefficient of uniformity and its density. If the soil is in a loose state and the opening size of filter is larger than the particle size, soil particles can pass through the filter easily. If the soil is in a dense state and the opening size of filter is equal to or smaller than the particle size, soil particles cannot pass through the filter because of forming stable bridge in the base soil.

According to Giroud (2010), the opening size determination for filter material has been expressed with the following equations:

For $C'_u \leq 3$:

$$O_F \leq (C'_u)^{0.3} d'_{85S} \quad \text{for a loose soil} \quad (2.7)$$

$$O_F \leq 1.5(C'_u)^{0.3} d'_{85S} \quad \text{for a medium dense soil} \quad (2.8)$$

$$O_F \leq 2(C'_u)^{0.3} d'_{85S} \quad \text{for a dense soil} \quad (2.9)$$

For $C'_u \geq 3$:

$$O_F \leq \frac{9 \times d'_{85S}}{(C'_u)^{1.7}} \quad \text{for a loose soil} \quad (2.10)$$

$$O_F \leq \frac{13.5 \times d'_{85S}}{(C'_u)^{1.7}} \quad \text{for a medium dense soil} \quad (2.11)$$

$$O_F \leq \frac{18 \times d'_{85S}}{(C'_u)^{1.7}} \quad \text{for a dense soil} \quad (2.12)$$

The density state of soil is expressed using the density index, I_D . It is also called 'relative density'. Calculation of relative density is as follows:

$$I_D = \frac{e_{max} - e}{e_{max} - e_{min}} \quad (2.13)$$

where: e is the void ratio of the soil, e_{min} is the minimum void ratio of the soil, and e_{max} is the maximum void ratio of the soil.

The related interval used for loose, medium dense and dense soil is as follows:

For the loose soil: $I_D \leq 35\%$

For the medium dense soil: $35\% < I_D < 65\%$

For the dense soil: $I_D \geq 65\%$

3. Porosity Criteria

Flow of liquid on any porous media creates flow channels. These channels are directly related with distribution of the opening size on the filter media, which is the number of opening size per unit area.

As all the criteria for geotextile filter comes from the general use of granular filter material, porosity and number of opening size per unit area of geotextile materials

have similarity with granular material. Thus, if the number of filter openings in a geotextile is at least equal the number of openings in a typical granular filter, the geotextile meets the requirements.

According to Giroud (2010), for woven geotextile the relative open area (A_R), which is the ratio of open area to total area, should be equal or greater than 10%. Also, for nonwoven geotextile the porosity (n) should be equal or greater than the 55%.

4. Thickness Criteria

This is the criterion valid only for nonwoven geotextile material. The thickness of the nonwoven geotextile affects the path that soil will travel through on it. This path is bounded by fibers, and the passage between fibers is called as “constriction”.

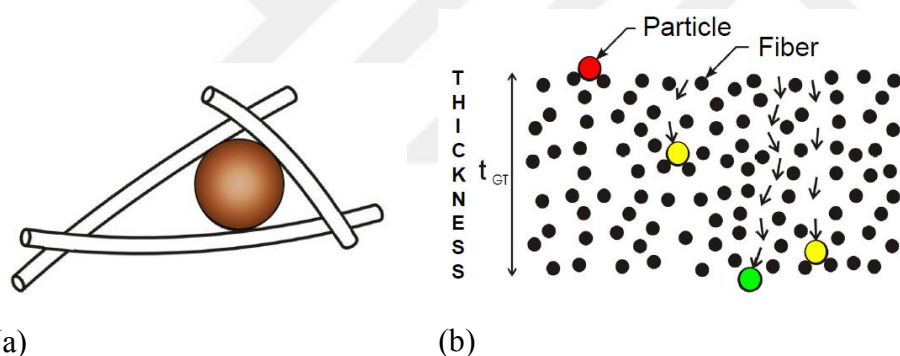


Figure 2.7 (a) a constriction in a geotextile (i.e. passage between fibers of geotextile), (b) Schematic view of cross section through a nonwoven geotextile, in which one particle stopped on top of the geotextile, two particles stopped inside the geotextile and one particle passing through it (Giroud 2010).

Each filtration path on the geotextile contains a number of constrictions, and the soil particles can go through these constrictions if they are smaller than the size of constriction. So, smallest constriction size on each filtration path defines the opening size of that path. Therefore, a geotextile filter should have needed effective constriction size in all filtration path to not face piping or clogging problem in structure.

To select and design the geotextile filter material properly, the thickness of the materials should be decided by the following equations (Giroud, 2010):

$$\frac{O_F}{d_f} = \frac{1}{\sqrt{1-n}} - 1 + \frac{1}{(1-n)t_{GT}/d_f} \quad (2.14)$$

$$\frac{O_F}{d_f} = \frac{1}{\sqrt{1-n}} - 1 + \frac{1}{\mu_{GT}/(\rho_f d_f)} \quad (2.15)$$

$$N_{constrictions} = \frac{\mu_{GT}}{\rho_f d_f \sqrt{1-n}} \quad (2.16)$$

where: O_F is the opening size of nonwoven geotextile, t_{GT} is the thickness of nonwoven geotextile, d_f is the used fiber diameter, μ_{GT} is the mass per unit area of the geotextile, ρ_f is the density of fiber material and $N_{constrictions}$ is the number of constrictions of geotextile. According to FEMA (2008), the value of $N_{constrictions}$ should be in the range of 25-40 for proper design of geotextile filter.

The four design requirements of geotextile, expressed by Giroud (2010) is summarized in the Table 2.3.

Table 2.3 Summary of geotextile filter criteria according to Giroud (2010)

1.Permeability Criteria	
$k_F \geq \max(k_S, i_S k_S)$	k_F = hyd. conductivity of filter k_S = hyd. conductivity of soil i_S = hyd. gradient in the soil next to the filter

Table 2.3 (continued) Summary of geotextile filter criteria according to Giroud (2010)

2.Retention Criteria

Density of Soil	Filter opening size, O_F
Loose	$O_{F \leq} (C'_u)^{0.3} d'_{85S}$
$C'_u \leq 3$ Medium	$O_{F \leq} 1.5 (C'_u)^{0.3} d'_{85S}$
Dense	$O_{F \leq} 2 (C'_u)^{0.3} d'_{85S}$
O_F= opening size of nonwoven geotextile C'_u= linear coefficient of uniformity $[C'_u = \frac{d'_{60}}{d'_{10}} = \sqrt{\frac{d'_{100}}{d'_0}}]$ d'_{85S} = the linear particle size of the soil that corresponds to 85% by mass	
Density states:	
Loose	$O_{F \leq} \frac{9d'_{85S}}{(C'_u)^{1.7}}$
$C'_u \geq 3$ Medium	$O_{F \leq} \frac{13.5d'_{85S}}{(C'_u)^{1.7}}$
Dense	$O_{F \leq} \frac{18d'_{85S}}{(C'_u)^{1.7}}$
$I_D \leq 35\%$, loose $35\% < I_D < 65\%$, medium dense $I_D \leq 35\%$, loose	

3.Porosity Criteria

$A_R \geq 10\%$, for woven geotextile $n \geq 0.55$ (%55) , for non-woven geotextile	A_R = relative open area (open area / total area) n = the prosity
--	--

4.Thickness Criteria

$\frac{O_F}{d_f} = \frac{1}{\sqrt{1-n}} - 1 + \frac{1}{(1-n)t_{GT}/d_f}$ $\frac{O_F}{d_f} = \frac{1}{\sqrt{1-n}} - 1 + \frac{1}{\mu_{GT}/(\rho_f d_f)}$ $N_{constrictions} = \frac{\mu_{GT}}{\rho_f d_f \sqrt{1-n}}$	O_F= opening size of nonwoven geotextile t_{GT}= thickness of nonwoven geotextile d_f= fiber diameter μ_{GT} = mass per unit area of the geotextile ρ_f = density of fiber material $N_{constrictions}$ = number of constrictions of geotextile *$N_{constrictions}$ should be in the range of 25-40 (FEMA,2008)
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2.6.2 Filter Criteria of Geotextile According to Luetlich et al. (1992)

According to Luetlich et al. (1992), besides the retention, permeability and anti-clogging criteria geotextile should be strong enough to survive its installation in the construction site and resistant enough to environmental effects for design life of the project. Actually, the design criteria for filters is based on the project's requirements. In accordance with Luetlich et al. (1992) design criteria and procedure for selection of proper filter material is detailed in this section.

1. Defining boundary conditions

Boundary conditions that are confining stress and flow conditions of the field should be determined and effects of them should be indicated accordingly. Confining stress of the soil near the geotextile filter has importance because it is directly related with soil index parameters such as density and hydraulic conductivity. Similarly, whether the flow condition is steady state or dynamic in soil media, it is essential for the retention requirements of filter accordingly.

2. Soil retention requirements

Defining of retention requirement starts with soil particle size distribution. The determination of the amount of gravel, sand, silt and clay in the soil is the first step for retention criteria. Atterberg limits, dispersivity of soil and density condition of soil has effect on maximum allowable geotextile opening size retention criteria and so retention criteria.

3. Anti-clogging requirements

Both permeability and retention requirements of a filter are related with size of the openings. Clogging of filter material affects those very important two requirements. To minimize the risk of clogging, the porosity of the geotextile and distribution of the open area should be identified. For that purpose, Luetlich et al. (1992) states that the opening size that satisfies the retention criteria should be selected as large as possible. In fact, the porosity (n) of nonwoven geotextile should

be greater than 30%, and the percent open area (POA) of woven geotextile should be greater than 4%.

4. Survivability and durability requirements

Survivability requirement is the criterion that taking account during installation of geotextile filter. In the case of heavy compaction drainage media, needed geotextile strength properties has been already shown in Table 2.1. Moreover, for durability of geotextile filter during service life of project, selected material should be resistant to environmental effects such as UV light.

Luittech et al. (1992) clearly states that, there are number of factors that affect the selection of geotextile for filtration purposes. Retention and permeability criteria mainly shapes the filter properties, however besides that boundary conditions and the internal stability of the soil has also important effect on design of a filter. For the case of dense soil and steady seepage, the design criterion defined by Luettich et al. (1992) is shown in Table 2.4.

Table 2.4 Geotextile particle retention criteria for dense soil and steady seepage according to Luettich et al. (1992)

Type of soil	Retention criterion
$D_{20} < 0.002 \text{ mm}$	$O_{95} < 0.21 \text{ mm}$
$D_{20} > 0.002 \text{ mm and } C'_u > 3$	$O_{95} < 18 \times \frac{d_{50}}{C'_u} \text{ mm}$
$D_{20} > 0.002 \text{ mm and } C'_u < 3$	$O_{95} < 2 \times C'_u \times D'_{50} \text{ mm}$

2.6.3 Filter Criteria of Geotextile Standard of ISO18228-3

In accordance to Standard of ISO18228-3 Design Using Geosynthetics in the part of filtration, the functional properties of geotextile relevant to design are explained such that: characteristic opening size, velocity index and permittivity, resistance to water penetration, number of constriction and percent open area. According to the standard specification, there are two types of geotextile material application as a filter based on filtration mechanism, which are:

- Filtration of soils: this is the type of soil and geotextile is in contact perfectly. Water flows through the soil media and drags the finest particles away depending on equilibrium condition between soil and geotextile
- Filtration of slurry: this is the type of soil particles accumulated in geotextile is suspended in water.

For the case of earth fill dam, the filter is in condition of filtration of soil. The needed requirements and design criteria of geotextiles as the filter material is shown in Table 2.5. The design criteria are valid for the filtration of soil condition and steady state flow conditions.

Table 2.5 Summary of geotextile filter criteria (ISO 18228-3)

Designing Geotextiles for Soil Filtration	
1.Retention Criteria (*)	
$COS \leq B \times D_I$	<i>COS</i>: Characteristic opening size <i>B</i>: Factor for application, soil properties and hydraulic conditions <i>D_I</i>: Indicative diameter of soil
Less than 50% silt ($d_{50} > 75\mu m$)	
For $C_u < 2$,	$B = 1$ and $D_I = D_{85}$
For $2 \leq C_u \leq 4$,	$B = 0.5 \times C_u$ and $D_I = D_{85}$
For $4 \leq C_u \leq 8$,	$B = 8/C_u$ and $D_I = D_{85}$
For $C_u > 8$, and linearly graded soils,	$B = 1$ and $D_I = D_{50}$
For $C_u > 8$, and concave upward gradation curves,	$B = 1$ and $D_I = D_{30}$
For $C_u > 8$, and gap-graded gradation curves,	$B = 1$ and $D_I = D_G$ where D_G is the minimum gap size
More than 50% silt ($d_{50} < 75\mu m$)	
For $PI \leq 5\%$,	$B = 1$ and $D_I = D_{85}$ and $COS \leq 300\mu m$
For $PI > 5\%$ and dispersivity $\geq 50\%$,	$B = 1$ and $D_I = D_{85}$
For $PI > 5\%$ and dispersivity $\leq 50\%$,	$COS \leq 800\mu m$

Table 2.5 (continued) Summary of geotextile filter criteria (ISO 18228-3)

2.Non-Retention Criteria (**)	
$COS \leq C \times D_j$	COS: Characteristic opening size C: Constant D_j: Indicative diameter of soil, for fines in suspension
For $C_u > 3$,	$C = 3$ and $D_j = D_{15}$
For $C_u \leq 3$,	COS should be selected as defined in the retention criteria part
3.Percent Open Area (POA)	
For coarse sands,	$POA > 4\%$
For fine, poorly graded sands,	$POA > 1.6\%$
For silty sands,	$POA > 0.5\%$
4.Permeability Criteria	
$V_F \geq E \times k_s \times i_s$	V_F: Indicative velocity of water passing through the filter, which is the flow rate divided by the total area of apparent area at water head of $\Delta H=0.05$ m E: Constant k_s: Permeability of soil i_s: Hydraulic gradient of soil
For high risk, e.g. Dams	$E \geq 1000$
For low risk, e.g. Low-rise geotechnical structures	$E \geq 100$
For very low risk.	$E \geq 10$

(*) $B = B1 \times B2$, depending on the hydraulic gradient and the soil density,

$B1 = 0.6$ in case of bidirectional flow;

$B1 = 0.8$ in case of hydraulic gradient $i > 5$;

$B1 = 0.1$ in case of hydraulic gradient $i \leq 5$;

$B2 = 0.8$ in case of unconfined soils;

$B2 = 1.25$ in case of dense and confined soils.

(**) $COS \geq 63\mu m$ if $D_{15} \geq 20\mu m$

$COS > 63\mu m$ for dynamic / turbulent flow

2.7 Filter Materials in Dams and Their Usage

Filter materials are used in dams for many purposes such as for drainage of water by controlling pore pressure in dam, for protection of base soil, to support the base material and avoid the cracking in the core. In this chapter, the drainage and filtration function of material will be discussed.

Some examples for filter materials that were used in dams are shown with red color in Figure 2.8. Actually, the geotextile can be used wherever the granular filter material is used in embankment dams. Geotextile can be used as chimney drain, blanket drain, chimney and trench filter.

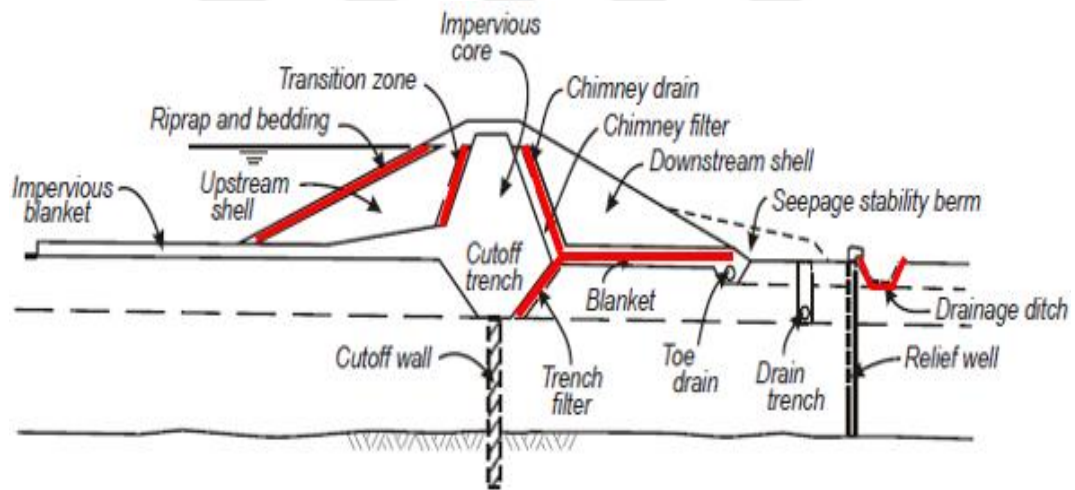


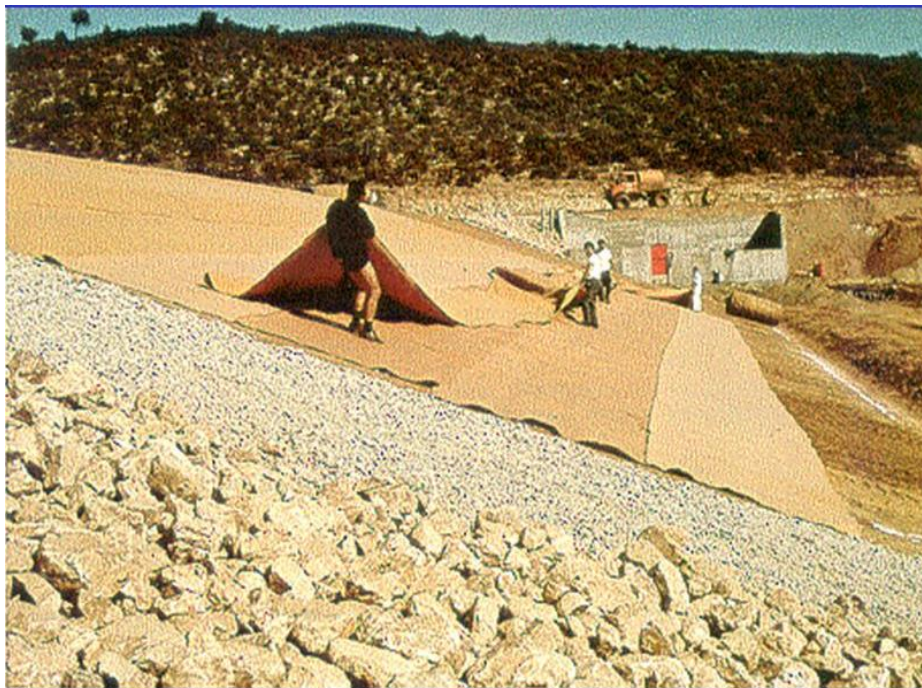
Figure 2.8 Representation of filters used in embankment dams (FEMA, 2011)

2.7.1 Examples of Geotextile Filters from Different Countries

The first use of geotextile in large earth dams as a filter material was in 1970 in Valcros dam in France (Faure, Farkouh, Delmas, & Nancey, 1999) (Figure 2.9a). It was a homogenous earth dam that is made with mainly silty sand soil.

In Valcros dam, the geotextile filters were used in two parts of the dam; one is around the drainage trenches at the bottom, and the other is under the rip-rap layer on the upstream slope (Artières, Oberreiter, & Aschauer, 1970). The double coat needle punched nonwoven geotextile with 300 g/m² was used. It was observed that there was a continuous drop of clean water leakage for 35 years.

Additionally, geotextile samples were taken from different part of the Valcros dam, and some experiments were conducted on them in the 6th and 22nd years after its construction. It was found that the tensile strength of the geotextile decreased slightly from 0 to 6 years (reduction amount is 10-20%), but there was no difference in tensile strength between 6th and 22nd years. Also, the hydraulic conductivity values were the same in the 6th and 22nd years, and less than 5% by weight of the grains attached to the filter over time (Faure et al., 1999).



a)



Figure 2.9 Application of geotextile in the a) upstream facing of Valcros Dam b) upstream and downstream of the Mogol Dam c) chimney drain of Samira Dam (Giroud, 2005)

Besides Valcros Dam, the geotextiles were used in several earth dams as a filter material such as Mogol Dam, Samira Dam and Montaubry Dam (Figure 2.9). Some examples for use of geotextile in earth dams, and geotextile properties are listed in Table 2.6.

Table 2.6 Examples of dams using geotextile for filtration purposes

Dam	Contry, Year	Height of Dam	Construction Type of Dam	Properties of Used Geotextile	Component in Dam
Valcros	France, 1970	18 m	Silty sand, %30 < 0.075 mm	Needle punched nonwoven geotextile, 300 g/m ²	Upstream, downstream and drainage
Mogol	South Africa, 1980	56 m	Clay core fill dam	Needle punched nonwoven geotextile, 340 g/m ²	Upstream, downstream and drainage
Montaubry	France, 2001	20 m	Homogenous earth fill dam	Thick triple geotextile nonwoven	Upstream, downstream and drainage
Samira	Nigeria, 2001	18 m	Very fine-grained laterite sand fill dam	Needle punched nonwoven geotextile, apparent opening size: 80μ	Upstream, downstream, chimney and blanket drainage
Sidi Ben Taiba	Algeria, 2003	64 m	Clay core fill dam	Needle punched nonwoven geotextile, apparent opening size: 80μ	Upstream, downstream and blanket drainage

CHAPTER 3

EXPERIMENTAL STUDY

3.1 Introduction

The present experimental work was carried out to to examine clogging potential and define the filtration compatibility of selected nonwoven geotextile and clayey type of soil filter systems in the laboratory. For this purpose, the gradient ratio test were conducted according to ASTM D5101 standard.

3.2 Used Materials In The Tests And Their Relevant Properties

3.2.1 Kayseri Clay – As Base Material

Kayseri clay obtained from the Technical Research and Quaility Control Laboratory of State Hydraulic Works (DSI) in Ankara was used as base material in the gradient ratio test. According to DSI technical specification of fill works (DSI, 2017), the impermeable fill materials used in earth dams should have maximum particle size of 75 mm and the soil should contain minimum of 10% of clay content (particle size smaller than 2 microns). Also, the plasticity index of the clay should be minimum 15%. Kayseri clay satisfies all the mentioned criterion.

The grain size distribution curve and general properties of Kayseri clay are given in Figure 3.1 and Table 3.1 respectively. All tests were conducted according to relevant ASTM standards. A falling head permeability test carried out on a well compacted Kayseri clay sample, and the permeability was obtained as 3.15×10^{-9} cm/s.

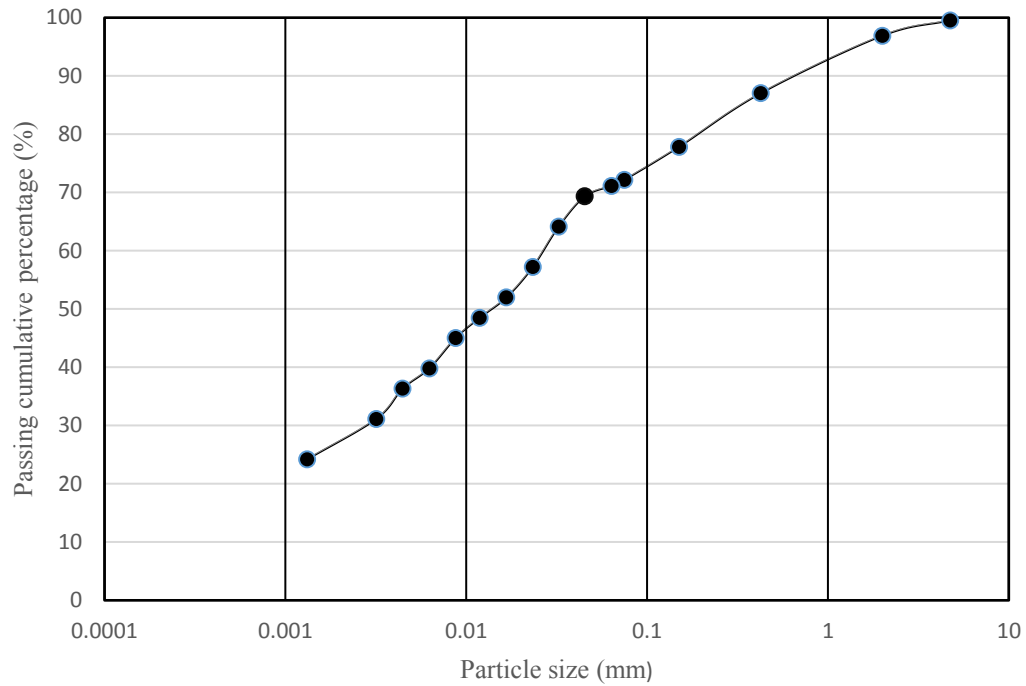


Figure 3.1 Grain size distribution curve of Kayseri clay

Table 3.1 Some Engineering and Index Properties of Kayseri Clay

Atterberg limits	Liquid limit (%)	44
	Plastic limit (%)	22
	Plasticity index (%)	22
Specific Gravity	Gs	2.73
Permeability	k (cm/s)	3.15×10^{-9}
Standard Proctor compaction test	Maximum dry density (g/cm ³)	1.58
	Optimum water content (%)	17.7
Soil classification name and symbol (USCS)	Fines content (%)	72
	Name & Symbol: Inorganic clays, silty clays, sandy clays of low plasticity , CL	

In the experiments, Kayseri clay was used as in well-compacted state to reflect the actual case of an earth dam.

3.2.2 Granular Mixture – As Filter Material

The mixture of granular filter material contains three different types of granular soil (see Figure 3.2). Two of them were obtained from the laboratory of State Hydraulic Works (DSI), and the other one were taken from METU Soil Mechanics Laboratory. To have desired granular filter criteria in accordance with DSI technical specification of fill works, three soils having different grain sizes were combined.



Figure 3.2 The photos of granular filter mixture materials a) coarse filter, b) fine filter and c) Çine sand

One of the soil taken from DSI lab were named as “coarse filter”, which contains particles having diameter from 4.75 to 37.5 mm according to sieve analysis (see Figure 3.3). The other soil was named as “fine filter”, which contains particles having diameter from 0.075 to 12.5 mm according to sieve analysis (see Figure 3.4). The last soil in the filter mixture was Çine sand that is taken from METU Soil Mechanics Laboratory. It contains particles with diameter from 0.075 to 2 mm according to sieve analysis (see Figure 3.5).

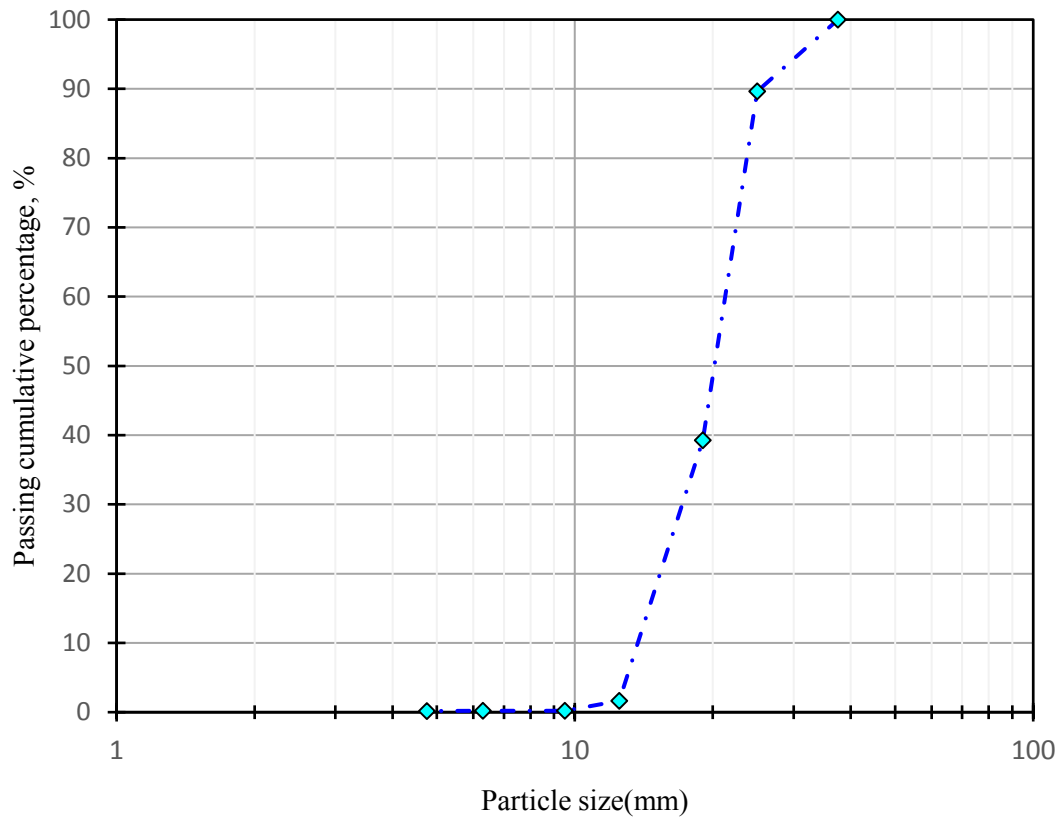


Figure 3.3 Grain size distribution curve of “coarse filter” material

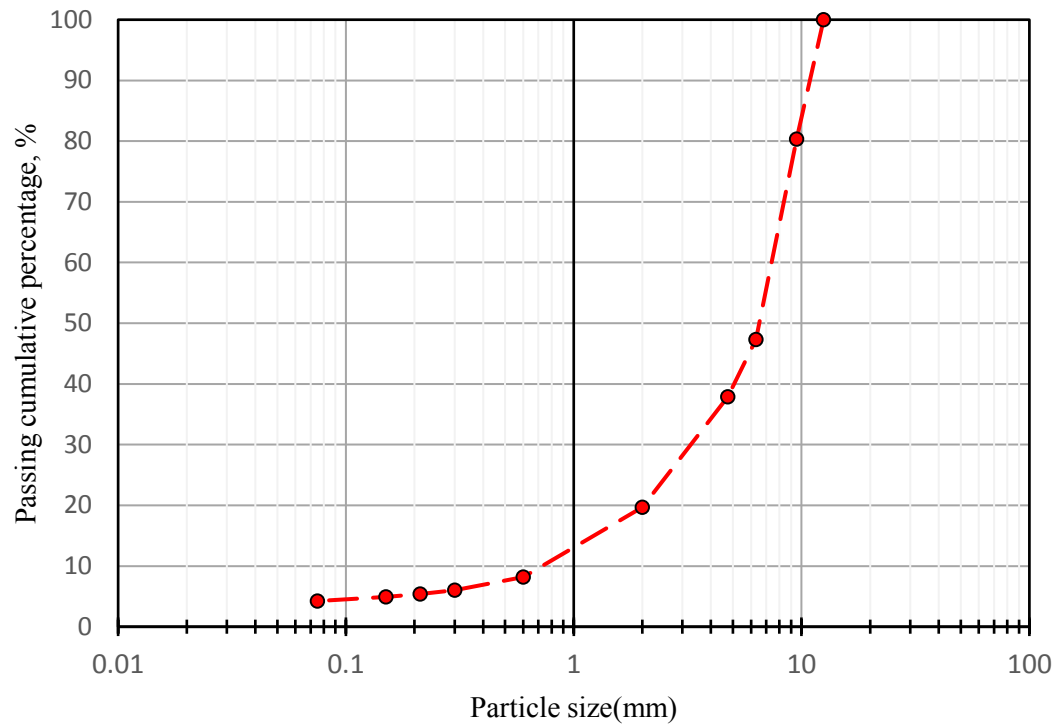


Figure 3.4 Grain size distribution curve of “fine filter” material

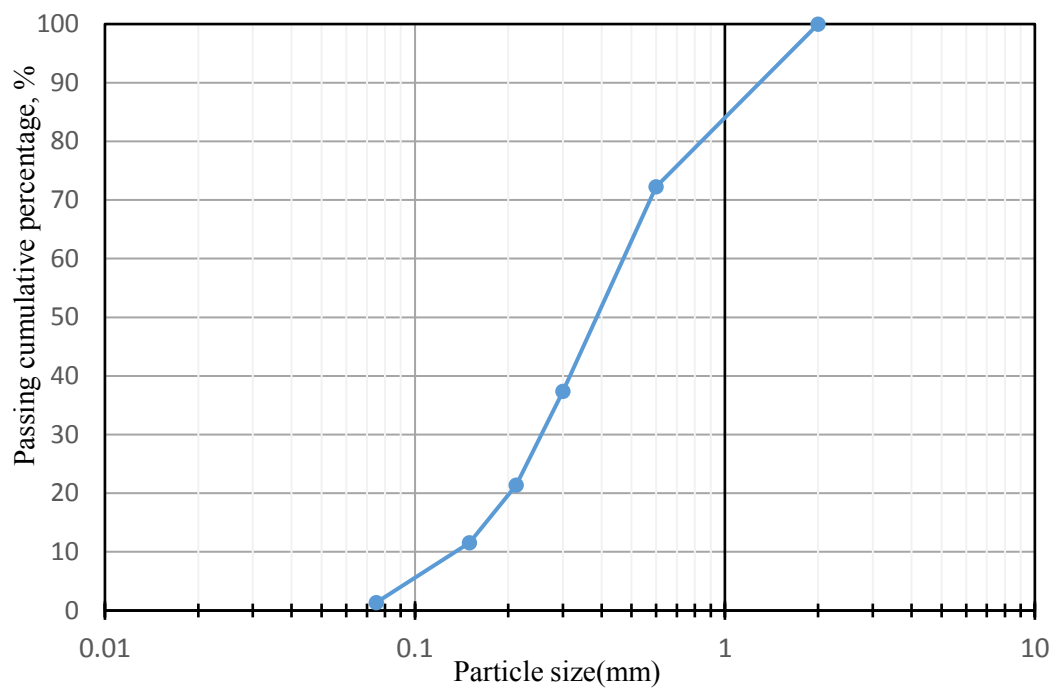


Figure 3.5 Grain size distribution curve of “Çine sand”

The mixture of granular filter was prepared with 40% of coarse filter, 50% of fine filter and 10% of Çine sand. The main point while determining the percentage of these three soils in the mixture is that the grain size distribution of the mixture should be in between the limit of maximum and minimum (boundaries) of grain size distribution of granular filter as stated in DSI technical specification of fill works. Sieve analysis test was conducted on prepared granular filter mixture, and grain size distribution curve is shown in Figure 3.6.

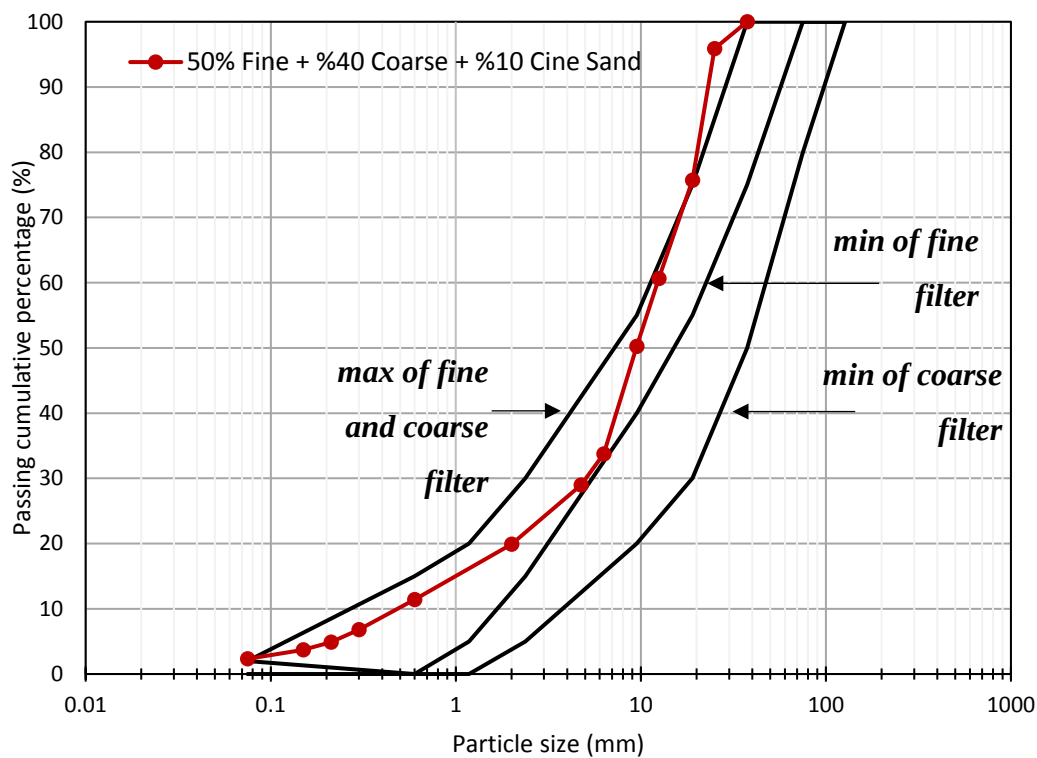


Figure 3.6 Grain size distribution curve for granular filter mixture and boundaries for allowable filter grain size distribution

According to the grain size distribution curve of filter material, the group symbol based on Unified Soil Classification System and the related parameters have been shown in Table 3.2.

Table 3.2 Properties of Filter Material

	D_{50}	9.5 mm
	D_{10}	0.55 mm
C_u (Coefficient of Uniformity)	$\frac{D_{60}}{D_{10}} = \frac{12.5}{0.55} = 22.73$	
C_c (Coefficient of Curvature)	$\frac{D_{30}^2}{D_{10} \times D_{60}} = \frac{4.8^2}{0.55 \times 12.5} = 3.35$	
Soil classification name and symbol	Poorly graded gravels, sandy gravels, with little or no fines GP	

3.2.3 Geotextiles – As Filter Material

Two types of geotextiles having different apparent opening size, thickness and mass per unit area were selected in accordance Giroud (2010) and Luettich et al. (1992) design criteria to examine the boundary conditions of geotextiles. Table 3.3 summarizes the results of applying these criteria to the soil used in this research.

Table 3.3 Selection Criteria of Geotextiles to use in experiments

	Giroud (2010)	Luettich et al. (1992)	ISO/CD TR18228-3
Apparent Opening Size (mm)	< 0.093 (loose) < 0.14 (medium dense) < 0.185 (dense)	< 0.21	< 0.39
Permeability (cm/s)	$k_F > 3.18 \times 10^{-8}$	$k_F > 3.18 \times 10^{-8}$	$V_F^* > 3.18 \times 10^{-5}$

* V_F is the indicative velocity of water passing through the filter, which is the flow rate divided by the total area of apparent area at water head of $\Delta H = 0.05$ m.

In the experiments, the geotextile specimens was trimmed to the diameter of 11.2 cm. Some of the tests were conducted with one layer of geotextile, and some of them were conducted with two layers of geotextile to see the effects of the number of layer for used geotextiles.

The sample taken from both types of geotextiles was oven dried for 24 hours. The weight of the geotextiles were measured before and after the drying process. 0.002% reduction in weight was observed for the TS40 type of geotextile, and 0.006% reduction in weight was observed for the PP3000 type of geotextile. The observed reduction rate in weight of the geotextiles are caused due to nature of the materials that make up geotextiles (i.e. the elements of carbon, hydrogen and oxygen). The reduction in the geotextiles' weight is considered while calculating piping rate of the system at the end of each test series.

Photo of used geotextiles is shown in Figure 3.7, and the properties of used geotextiles are shown in Table 3.4. All the values are given by the manufacturers.



a)



b)

Figure 3.7 Photo of used geotextiles a) TS40 and b) PP3000

Table 3.4 Properties of Used Geotextile

Property	Unit	Type of the Geotextile	
		PP 3000 Nonwoven Geotextile	TS40 Nonwoven Geotextile
Mass per unit area	g/cm ²	300	180
Thickness	mm	2.4	1.8
Apparent Opening Size	mm	0.077	0.1
Permittivity	mm/sec	70	125
Tensile Strength	kN/m	17	14
Cone drill drop test (hole-Ø)	mm	16	24
Puncture Strength (Static)	N	2700	2100
Elongation	%	Minimum 50	Minimum 46

3.3 Filter Experiments

3.3.1 Test Set-up

The gradient ratio test apparatus used in this research is designed and manufactured at METU Civil Engineering Department. The setup is composed of soil geotextile permeameter cells, two containers for inflow and outflow water, a balance, wire mesh screen for geotextile, rubber gaskets, manometer board, manometer tubes, connecting holes on permeameter cells, and flexible hoses for head measurement port and manometer tube connections.

The layout of the test set-up is shown in Figure 3.8, and the photo of test set-up is shown in Figure 3.9.

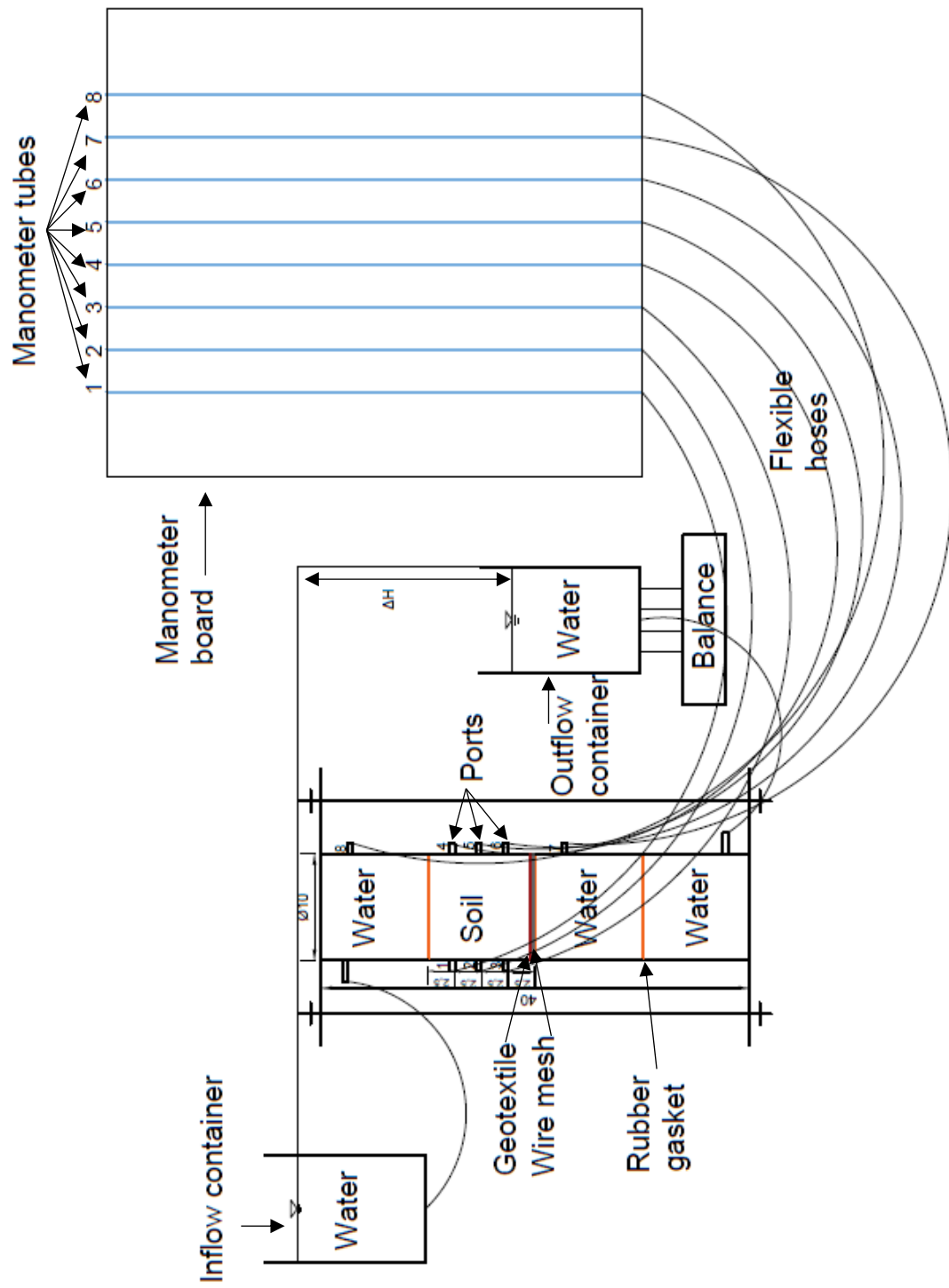


Figure 3.8 The layout of test set-up

*All dimensions are in cm.



Figure 3.9 Photo of the test set-up

3.3.1.1 Soil-Geotextile Permeameter Cells

Special permeameter cells were made of plexiglass. The permeameter consists of four cylindrical plexiglass parts, and they are connected to each other (see Figure 3.10).

Each plexiglass cylinder cell has a height of approximately 10 cm. Because the height of the soil sample affects the water elevation head to have desired hydraulic gradient in the standard of ASTM D5101, it is limited to 10 cm in maximum. The inside diameter is 10 cm as described in standard of ASTM D5101 (ASTM, 2012). As the diameter of the permeameter section is greater than 10 times the size of the largest particle size of the soil (i.e. $d_{100} = 4.75$ mm), the test results cannot be influenced by the walls of the permeameter (ASTM, 2012).

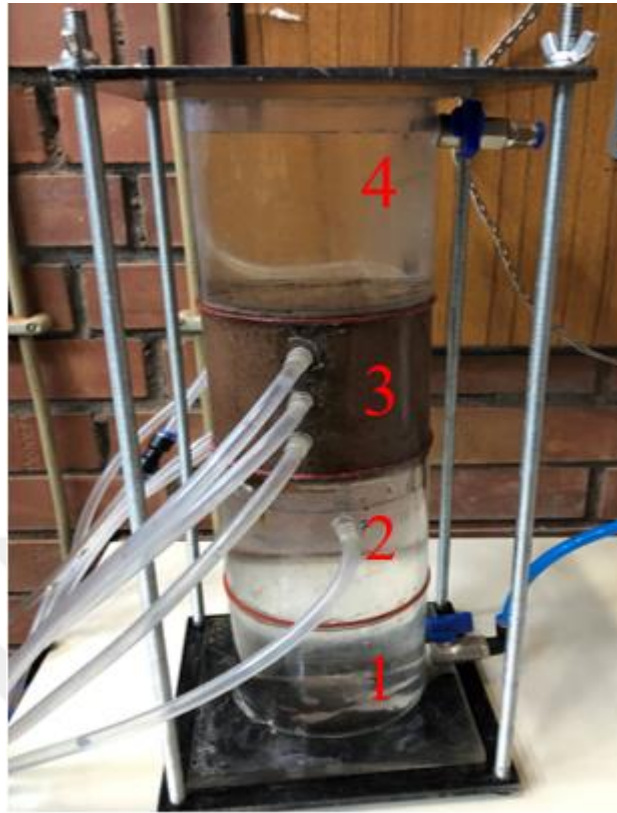


Figure 3.10 Soil-geotextile permeameter cells

The 1st cell of the permeameter is designed for collecting the particles passing through geotextile.

The 2nd cell of the permeameter is equipped with a wire mesh to support soil-geotextile composite system, and one port is used just below the wire mesh to measure water head over there (see Figure 3.11).

The 3rd cell of the permeameter is designed with 6 head measurement ports on it. The ports are located in opposite direction of same level in groups of three (Figures 3.8 and 3.9). They are used to monitor the water head at various elevations in soil along the flow path. Each port is connected to the manometer tube which are mounted on a wooden board on the wall.

The inside mouth of the manometer ports on the wall of the cell 3 is covered with a mesh with an opening of 0.045 mm (No. 325) to prevent soil particles migration into the manometer tube. The coverage of inside of the manometer ports is advised

with No. 100 mesh in standard of ASTM D5101, however, the used soil in the experiment (Kayseri clay) mostly has the particles lower than 0.075 mm (No. 200). Therefore, the mesh is selected as lower opening area than stated in ASTM standard.



Figure 3.11 Permeameter with wire mesh used to support geotextile

The 4th cell of the permeameter is used for application of a constant head boundary condition to the top of the specimen, and also it has one port on it to measure the water head at that location.

To prevent water leakage through the system, rubber gasket is placed in between each permeameter cells. Also, all parts of permeameter are fixed with metal rods with a top and bottom cap. It is equipped with a support stand and brackets.

3.3.1.2 Head Measurement Ports

In total, eight head measurement ports are used to measure the water head at different locations in the system.

The port that is mounted on the 4th cell of the permeameter is numbered as Port 8 (Figure 3.8), and it is used for measuring the water head on the soil surface. The distance between the soil surface and the Port 8 is designed to prevent disturbance of soil surface due to local flow out of Port 8.

The Port 7, which is on the 2nd cell of the permeameter, is used for measuring the head of water after flow through soil-geotextile system.

Port 1 through Port 6 measure the water head at different elevations in the soil layer. These ports are mounted on the 3rd cell of the permeameter as it is seen in Figure 3.10.

The elevation difference between each pair of ports are equal, and it is 25 mm. In the calculation phase of gradient ratio, it is important that the water head measured at the manometers located 25 mm and 75 mm above the geotextile. Therefore, the Ports 1&3 and Ports 4&6 are located in distance between them 50 mm, and the distance of Port 3&6 from top of the geotextile is 25 mm. Ports 2 and 5 are additional ports, which gives more detailed information about the water head distribution, and the soil sample uniformity both in horizontal and vertical direction.

3.3.1.3 Manometer Tubes and Wooden Board

All the pressure head measuring ports are connected with vertical glass tubes placed on the wooden board (see Figure 3.8 and Figure 3.9). The wooden board is covered with scaled paper to measure water heads on the tubes during testing. Each head measurement port on the permeameter cell are connected to manometers on the board with flexible hoses.

3.3.1.4 Containers for Inflow and Outflow of Water

Two containers were used for inflow and outflow of water. They are used to maintain water heads and desired hydraulic gradient according to ASTM D5101 standard. One of the container was located on support stand, and the other one was located in the balance. With changing water elevations in the containers during testing, desired hydraulic gradients were obtained. To simulate field conditions in the laboratory, some assumptions and simplifications is accepted, and the system is designed to impose hydraulic gradients from 1 to 10 during the testing.

The test water introduced into the apparatus should be deaired, and should be maintained between 16 and 27 °C during the testing (ASTM, 2012). Air clogging can be decreased by using deaired water in the test. It is essential that use of deaired water in the experiment reduce the risk of forming air bubbles within the test set-up.

3.3.2 Soil Sample Preparation

Kayseri clay was prepared with Standard Proctor compaction at optimum water content in the 3rd cell of the permeameter. This method was used to simulate actual case of earth dam construction stages in the laboratory the clay has been compacted.

The soil sample has a diameter of 10.0 cm, and the height is 10 cm. The compactive effort can be calculated using the Equation 3.1, and for the case of Standard Proctor compaction the compactive effort is 593 kJ/m³ (Al-khafaji, 2016). To have same energy on the soil the required number of drops have been calculated as 20 using Equation 3.1.

$$C.E. = \frac{Ht. of Drop(m) \times Wt. of Hammer(kg) \times \# of Drops \times \# of Layer}{Volume of Mold(m^3)} \quad (3.1)$$

3.3.3 Test Procedure

3.3.3.1 Permeameter Assembly and Setup

First of all, all the permeameter sections are cleaned and dried. The selected nonwoven geotextile is trimmed to a diameter of 11.2 cm, then allowed to rest in de-aired water for about 2 hours to have fully saturated geotextile. Kayseri clay is compacted with having optimum water content and maximum Standard Proctor dry density into the 3rd cell of the permeameter.

As stated in the specification of ASTM D5101 (ASTM, 2012), the soil preparation procedure is very important step, and it may significantly influence the test results. In the standard, there are some techniques described for the soil placement into the permeameter unit, which are pluvation, slurry deposition and dry method technique. However, it is stated that the appropriate soil placement technique should be determined for the purpose of having field conditions in the laboratory. Therefore, the compaction method is selected as a soil placement method to have an impervious layer of the earth fill dam in the laboratory test set up.

The 1st and 2nd cell of permeameter placed on top of each other with placing lubricated rubber gasket in between them. The tested geotextile is placed over a wire mesh that is on the 2nd cell. The 3rd cell which contains already the compacted Kayseri clay specimen is placed on top of the 2nd cell. After the 4th cell of permeameter is placed on them the support stand is clamped with brackets and metal rods. While preparing the permeameter test set-up, the junction part of the permeameter sections are greased, and also greased rubber gasket is placed in between each pair of permeameter cells.

3.3.3.2 Saturation of Geotextile-Soil System

Head measuring ports are connected to manometer tubes on the wooden board with flexible hoses. In the beginning of saturation process, all the head measurement

ports except the Port 7 are in the close off position. The inflow container is not full with water at this stage. However, the top valve (inflow container valve) is in open position to out the air in the permeameter while water raising in the cells. The permeameter units are filled with de-aired water by the bottom valve (outflow container valve) till the elevation of Port 7, then the Port 7 also is became in close off position. It is allowed to raise in water level through the inflow container till the top vent valve to saturate soil-geotextile system.

As the flow direction is from bottom to top, permeability of sytem is not affected while saturating the soil-geotextile system. The bottom to top flow saturation procedure is also preferred to prevent soil migration through the tested geotextile. With this technique air bubbles formation and internal soil movement can be prevented (ASTM, 2012).

To ensure saturation process is completed properly, from top to bottom flow should not occur in the system, and the head measurment port pairs in the same elevation should show the same water level in the tubes. After reaching the water at top valve, both top and bottom valve should be close off, and the system is rested overnight to saturate soil-geotextile system very well.

Before starting the test, check the manometer tubes whether there is any air bubbles or not. If air bubbles are formed in the tubes, take the tube from the manometer board and lower the tube for water and air bubbles flow out.

3.3.3.3 Test Operation

After finishing permeameter assembly and saturation process, the inflow container is filled with de-aired water to have first desired hydraulic gradient for system, which is 1 for this testing. Top and bottom valves are opened and flow is started. Data is collected simultaneously.

Recorded data for each hydraulic gradient is that the date and time of test performed, the weight of the outflow container to calculate flow rate, water levels

at each manometer tubes, and the temperature both in inflow and outflow containers. Data is recorded at every 15 minutes for the first hour, then it is continued with the time period of 30 minutes, 1 hour, 2 hours, 4 hours, 8 hours. According to ASTM D5101 standard, the test schedule for data collection is defined as follows;

For $i=1$ test period is maximum 48 hours or until stabilization,

For $i=2.5$ test period is maximum 2 hours or until stabilization,

For $i=5$ test period is maximum 46 hours or until stabilization,

For $i=7.5$ test period is maximum 2 hours or until stabilization,

For $i=10$ test period is maximum 46 hours or until stabilization,

Stabilization term refers to the condition having constant outflow rate during the testing. In this experiment process, time period is selected as 24 hours for the system hydraulic gradient of 1, 5 and 10, since it is observed that the constant outflow rate is achieved within this period.

After 24 hours, while the outflow container remains constant at its position, the water elevation in the inflow container is changed to have second planned hydraulic gradient for the system. At this stage all the manometer ports is positioned close off, and reopened them after raising the water head in the inflow container. This operation is needed to prevent soil disturbance around manometer ports due to increasing of system hydraulic gradient.

During test, the water height difference in between inflow and outflow container (i.e. ΔH) should be constant to achieve desired hydraulic gradient for the system. For this test set-up, top container (inflow container) was feeded with additional de-aired water while water flow through the system. Raising in the bottom container (outflow container) was measured as in the range of 0.00015 to 0.00018 mm/hr for both of the used geotextile types. Therefore, the system is assumed to in constant head difference condition.

All measurement and data collection are done for all specified hydraulic gradient of 1, 2.5, 5, 7.5 and 10 accordingly. Also, as it is stated in the specification of ASTM

D5101 (ASTM, 2012), once the test is started, it should be performed without stopping at any time. The test should be run continuously until achieving the steady-state conditions or defined needed time for each hydraulic gradient. Moreover, some of the tests continued for longer time with a hydraulic gradient of 10 in order to collect data on the long-term performance of the soil-geotextile system.

3.4 Interpretation of the Test Data

The hydraulic gradient of the system and soil, the permeability of soil-geotextile system and the permeability of soil in it, the flow rate of system and the gradient ratio were analyzed with obtained test data. According to ASTM D5101 standard (ASTM, 2012) the formula for each of the parameters is shown in the following equations.

The target hydraulic gradient to be given to the system is known, however it can be calculated as the exact value with Equation 3.2.

$$i_{m-n} = \frac{h_m - h_n}{l_{n-m}} \quad (3.2)$$

Where; h_m represents the water head on piezometer m, and l_{n-m} is the thickness of the soil between manometers being analyzed (both in cm).

Hydraulic gradient is used for calculation of permeability of system and permeability of soil in it (Equation 3.3). In the testing procedure, the hydraulic gradient for soil-geotextile system is represented by i_{87} , and the hydraulic gradient for soil is represented by i_{46} (where the subscript numbers refer to port numbers in Figure 3.8). Also, the permeability values for the system and the soil are represented by k_{87} and k_{46} respectively. The permeability is calculated according to Equation 3.3. The equation gives value corrected to 20 °C.

$$k_T = \frac{V}{iAt} \times \frac{1}{100} \times \frac{\mu_T}{\mu_{20}} \quad (3.3)$$

Where; k_T is the permeability at temperature of the test (m/s), V is the volume of the measured flow (cm^3), i is the hydraulic gradient for which the system (i_{87}) or soil (i_{46}), A is the cross-sectional area of the soil specimen (cm^2), t is the time needed to collect a volume of water V (s), μ_T is the water viscosity at temperature of the test, and μ_{20} is the water viscosity at 20 °C.

The flow rate is another important parameter for the testing. With the flow rate analysis, clogging potential of soil-geotextile system can be analyzed. The flow rate is represented in cm^3/s , and measured by collected volume of flow in a definite time interval.

Gradient ratio (GR) is a key point to interpret the test data. It is defined in the ASTM D5101 as the ratio of hydraulic gradient in the contact zone of the geotextile-soil to hydraulic gradient in the soil. Gradient ratio is calculated with Equation 3.4.

$$GR = \frac{i_{37}}{i_{13}} = \frac{i_{67}}{i_{46}} = \frac{h_3 - h_7}{25} \times \frac{50}{h_1 - h_3} = \frac{h_6 - h_7}{25} \times \frac{50}{h_4 - h_6} \quad (3.4)$$

Where; i_{37} and i_{67} are the hydraulic gradient measured between the Port 7 and the Port 3 and Port 6 which located at 25 mm above the geotextile, i_{13} is the hydraulic gradient measured between the Port 3 and Port 1 which are located at 25 mm and 75 mm respectively, i_{46} is the hydraulic gradient measured between the Port 6 and Port 4 which are located at 25 mm and 75 mm respectively, h_3, h_6 and h_7 are the water head measured in the Port 3, Port 6 and Port 7 respectively.

In the formula 25 represents the 25 mm distance in between the geotextile and the port, and 50 represents the 50 mm distance in between the port located at 75 mm and 25 mm on the permeameter.

Gradient ratio is calculated for each specified hydraulic gradient value during the test. Moreover, GR should be analyzed for two sets of manometers located face to face on the permeameter cell. It is essential to detect pressure differences from one side to the other side. It gives some idea about air bubbles, algae, plugging in

manometer tube or in port, if there are significant differences in between manometers in terms of gradient ratio.

As stated in ASTM D5101 standard (ASTM, 2012), a gradient ratio GR value should be 1.0 (or slightly less is preferred) to not have any clogging problem.

The value of GR with less than 1.0 indicates that some soil particles migrate in the system and the filter bridge of the soil adjacent to geotextile has larger porous media in it.

On the other hand, a value of GR greater than 1.0 indicates that piping have occurred in the soil-geotextile system. The value of 1.0 is expected value for GR. However, the values for GR and related flow rates can be specialized for each site application. System can be in equilibrium in terms of flow and retaining soil, even if the GR value is greater than 1.0.

Studies show that permeability ratio, which is K_R , is also important parameter for the gradient ratio test results (A. H. Aydilek & Edil, 2003). K_R is defined as the ratio of the permeability of the soil to the permeability of soil-geotextile system. According to Aydilek and Edil (2003), K_R can improve the definition of clogging potential especially for fine grained soils, and its limit is defined as $K_R=3$ for acceptable clogging. Beside the GR, K_R was also analyzed for each test series.

At the end of each test series, the passed soil particles through the geotextile is collected in the bottom unit of the permeameter, and weighed after they are dried. Also, the geotextile should be oven-dried after a test is conducted successfully. Then, the mass of the oven-dried geotextile is compared to the initial mass of the geotextile before testing to determine the amount of soil retained on the geotextile. The mass of soil particles retained in and passed through the geotextile is used to represent the percentage of migrated soil particles relative to the total mass of soil sample used in the permeameter. Also, the piping rate for all testing system was defined.

3.5 Results

The gradient ratio test series have been conducted with 5 soil-geotextile and 1 soil-granular filter system. The type and properties of the used materials are summarized in Table 3.5. Geotextile TS40 has 180 g/cm² mass per unit area, 1.8 mm thickness and AOS of 0.1 mm, whereas PP3000 has 300 g/cm² mass per unit area, 2.4 mm thickness and AOS of 0.077 mm, other properties can be seen in Table 3.4.

Table 3.5 Properties of conducted experiments

Exp.	Used Geotextile	Mass of geotextile*, (g)	Density of Soil Specimen**, ρ (g/cm ³)	Preparation Water Content of Soil Specimen, w (%)
T1	1 Layer of TS40	1.87	1.22	8.2
T2	1 Layer of TS40	1.96	1.59	17.7
T3	2 Layers of TS40	1.58 & 1.77	1.57	17.0
T4	1 Layer of PP3000	3.60	1.58	17.5
T5	2 Layers of PP3000	3.64 & 2.93	1.60	19.1
T6	Granular Filter	-	1.59	17.8

* mass of about 11 cm diameter geotextile used in experiments

**represents the dry density of Kayseri clay

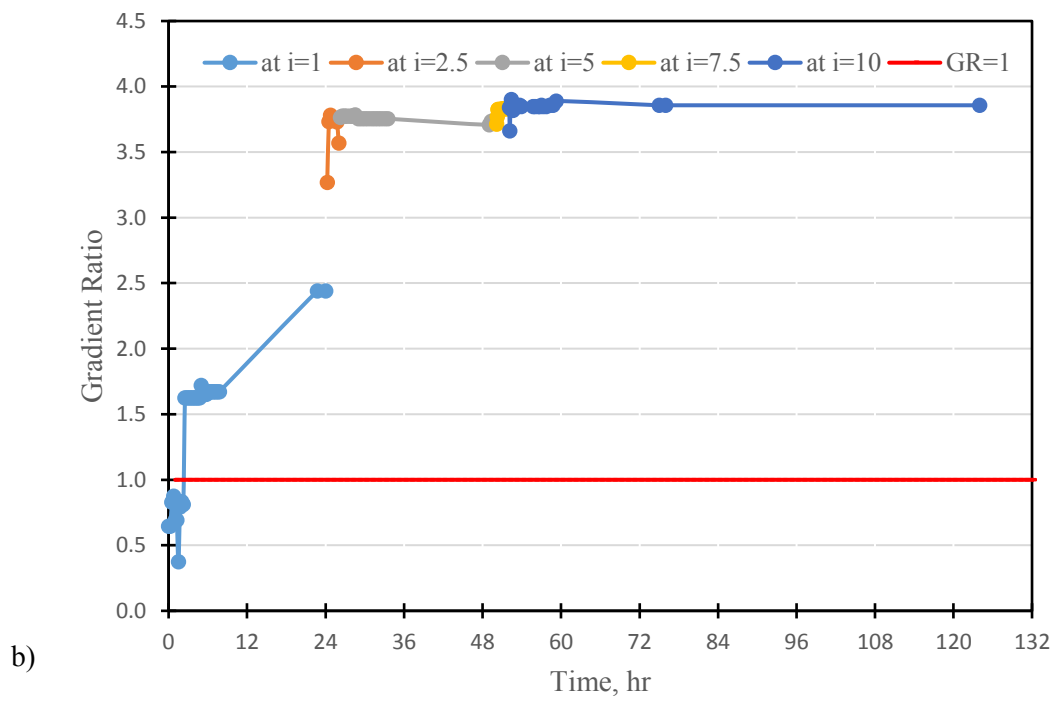
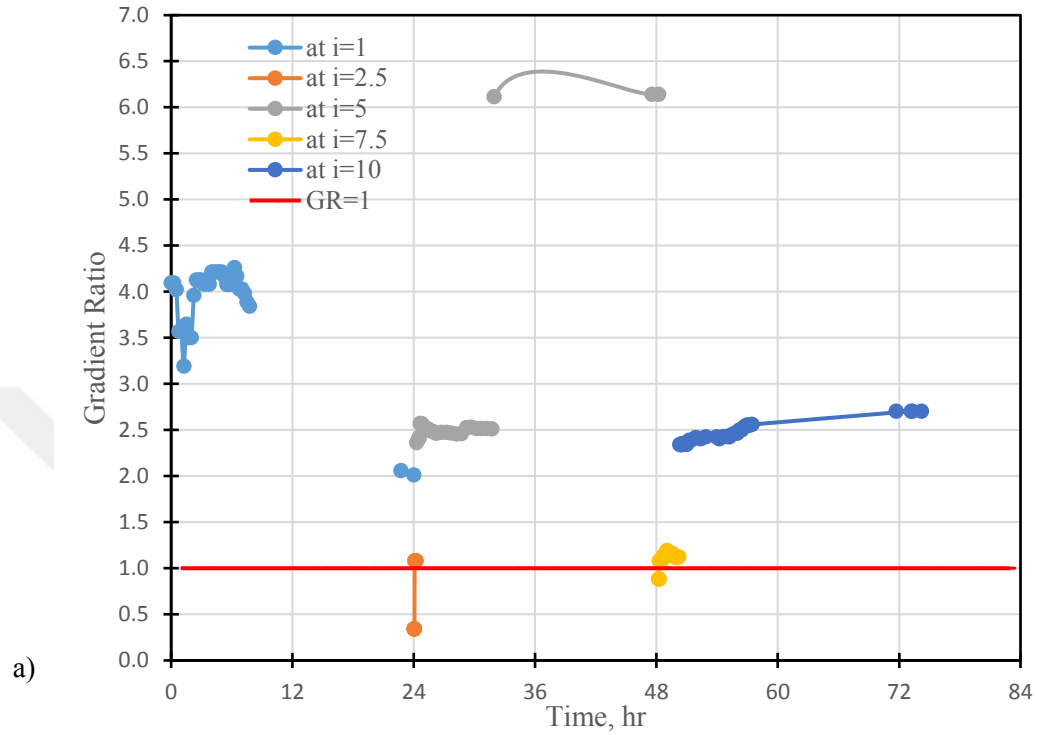
The test series are called as T1, T2, T3, T4, T5 and T6. The test T1 and T2 were conducted with one layer of TS40 geotextile and Kayseri clay with loose and dense state respectively.

The results are summarized and reported for the gradient ratio, permeability ratio, permeability of the soil, permeability of the soil-geotextile system, and piping rate of system according to retained and passing soil particles.

3.5.1 Experiments with Using Type TS40 Nonwoven Geotextile

First of all, the results for experiments T1, T2 and T3 are reported. In Figure 3.12, variation of the gradient ratio (GR) values for the experiments T1, T2 and T3 is

shown. The loose density state of soil in the test T1 was prepared by reducing preparation water content.



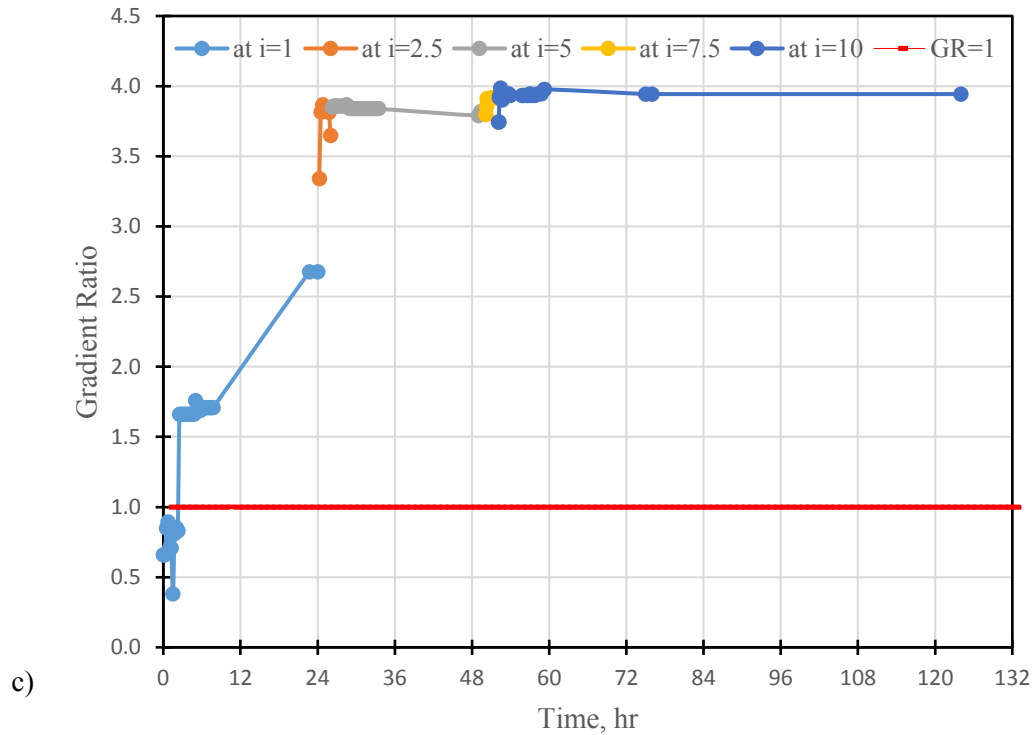


Figure 3.12 Temporal characteristics of gradient ratio with time, for experiment a) T1, b) T2 and c) T3

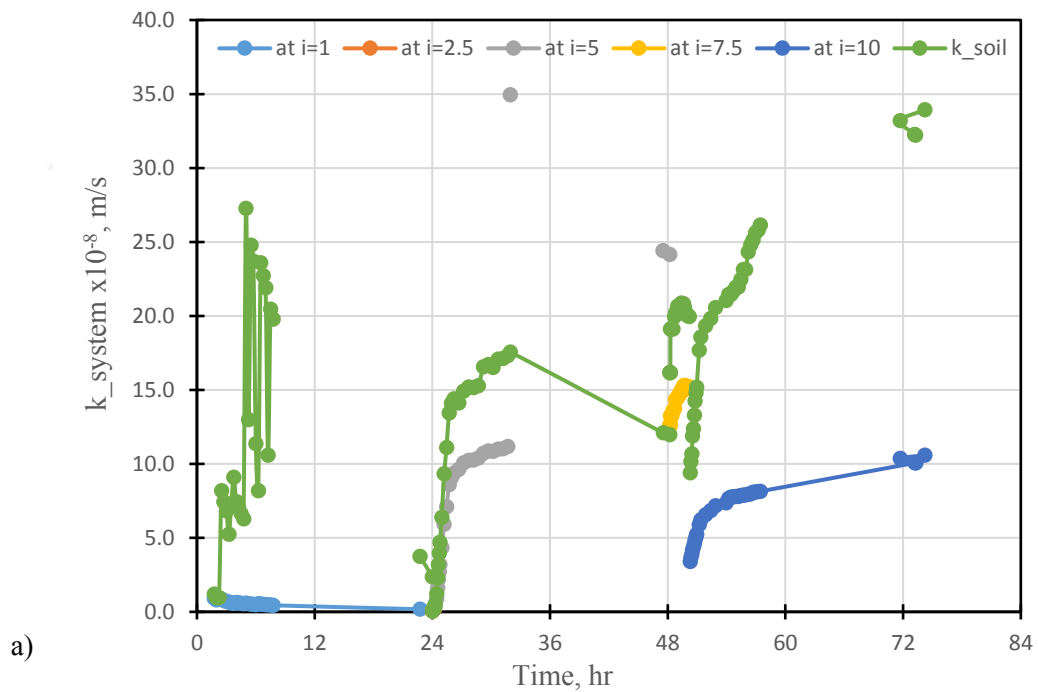
As seen in Figure 3.12 the GR value for the experiment T1 vari in the range of 0.5 to 6.5 at different hydraulic gradients. For T1, the GR value was around 4 in the beginning of the test, and the value decreased gradually. This indicates that, while filter cake is formed in the system some particles move in the system and according to ASTM D5101, piping occurs. However, the GR value gets close to the limiting value, which is 1, with increasing hydraulic gradients, at a certain time. For hydraulic gradient of 10, the GR value reached about 3, which showed that piping took place again in the system with passage of time.

On the other hand, for both experiments T2 and T3, the GR value vari in between 0.5 to 4. In this testing, GR values were 0.5 at the beginning of the test. GR significantly increased with increasing hydraulic gradient up to $i=2.5$, then GR values showed more stable behavior at higher hydraulic gradients. According to ASTM D5101, at $i=1$ the experiments T2 and T3 started to form filter cake and

migration of particles occurred mostly in this time period. When hydraulic gradient is increased, GR values also increased and piping in the system was analyzed.

For the experiments T2 and T3, the gradient ratio reached its maximum value, and there was no change with time and with increasing hydraulic gradient. However, the gradient ratio value changed with changing hydraulic gradients in the experiment T1. Therefore, density state of the soil specimen affects the system positively in terms of reaching to and keeping the steady state condition in the system. In other words, when T1 and T2 tests are compared, the only difference is the density of the soil. T2 test has denser soil; and as the density of soil increases, system reaches steady state condition in short time.

Figure 3.13 presents the change in permeability of soil-geotextile system for the experiments T1, T2 and T3.



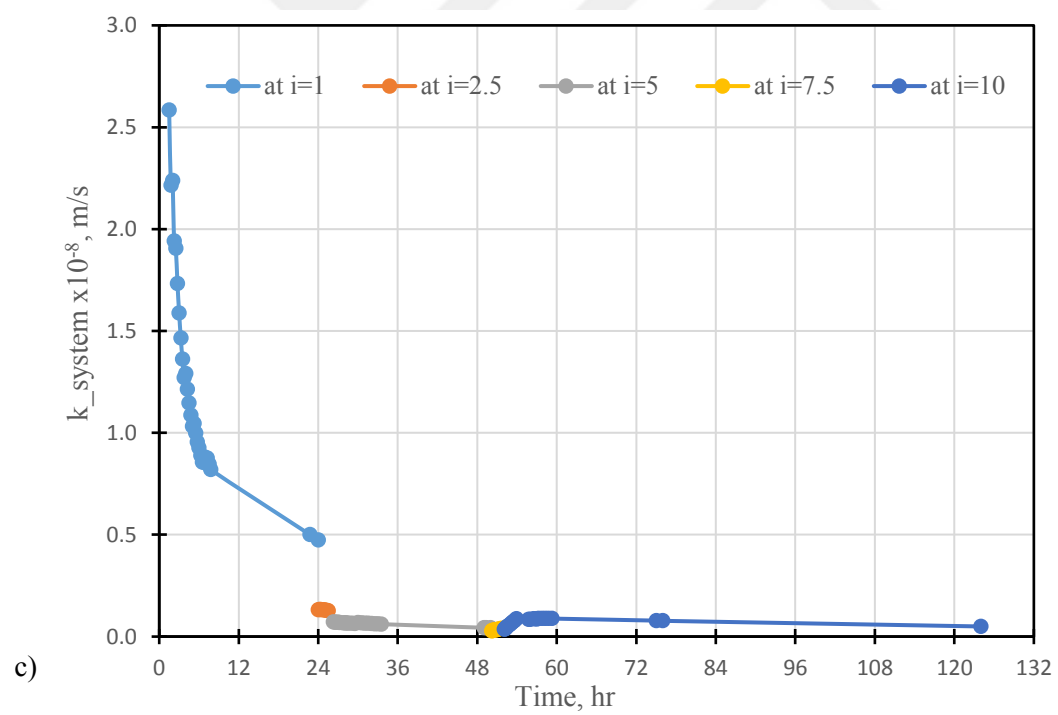
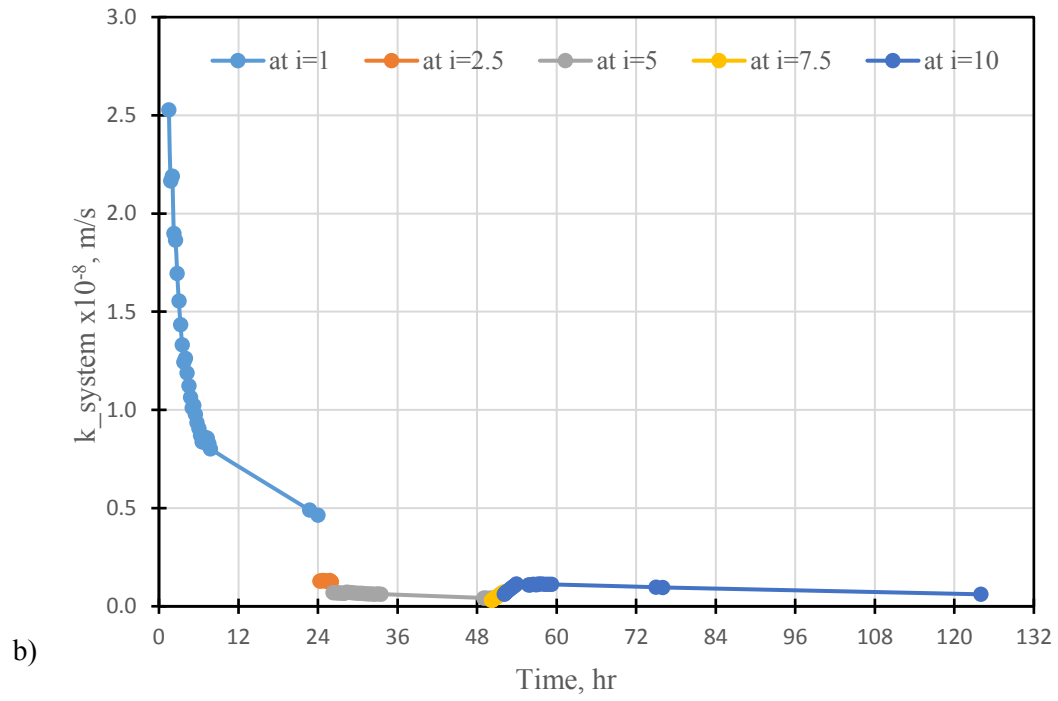


Figure 3.13 Temporal characteristics of system permeability with time, for experiment a) T1, b) T2 and c) T3

Equivalent permeability of the system had also similar behavior as gradient ratio for all of the cases T1, T2 and T3. In experiment T1, equivalent permeability of the system varied with time and change in hydraulic gradients. Equivalent permeability of the system was 0.91×10^{-8} m/s in the beginning of the test, and it decreased till the $i=5$ like GR values. Achieving steady state took longer time in the T1 test series. Also, both soil and equivalent permeability of the system changed rapidly with changing hydraulic gradients, then it tended to increase with time passing.

Almost for every hydraulic gradient, the soil permeability was greater than the equivalent permeability of the system for the experiment T1. It implies that there might be a blinding in the soil, so the permeability of sytem (k_{system}) was less than the permeability of soil (k_{soil}). For experiment T1, k_{soil} represents the permeability of soil layer in between port 4 and port 6.

For the experiments T2 and T3 soil permeability is given in more detail in Figure 3.14. When compared with the behavior of permeability of system and soil, in denser state achieving steady state was obtained earlier than loose state. It shows that the time required to have steady state and analyze actual behavior of system for relatively loose state or noncompact slurry case is more than stated in ASTM D5101.

In nature, soil permeability does not change with hydraulic gradient and time. So, the permeability of system should not show excessive change after reaching equilibrium, which is steady state in these test series. If the permeability changes with hydraulic gradient and time, there might be a problem in the test conditions like biological growth in the water.

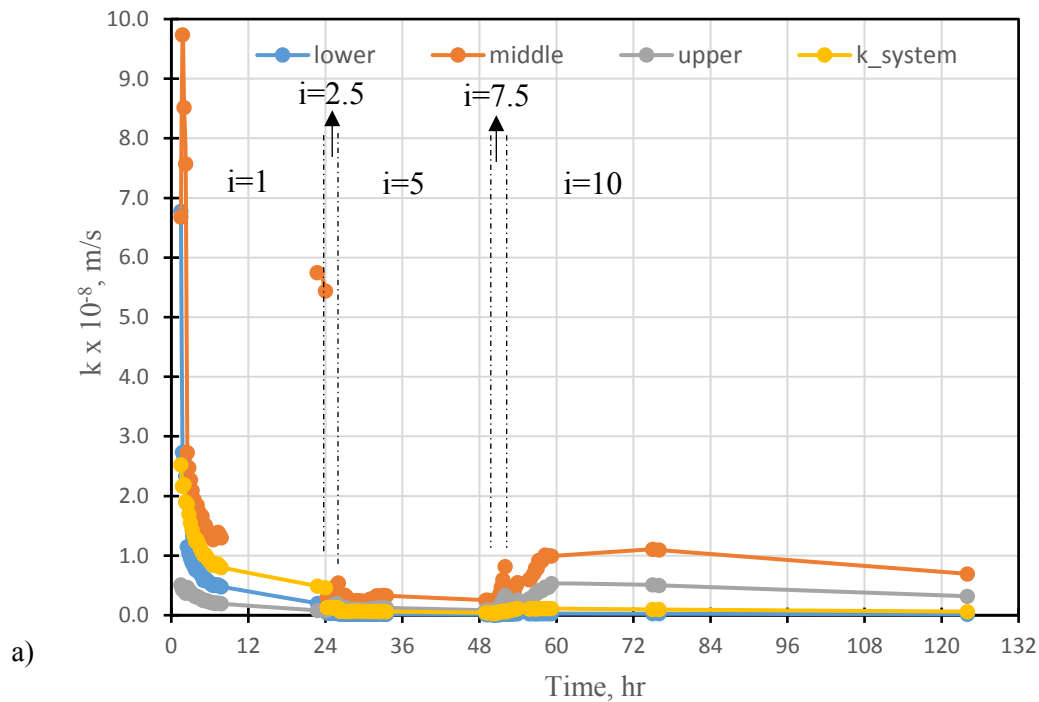
In the experiments T2 and T3, once the system reached at equilibrium condition, the system permeability saved its pattern. At $i=2.5$ and so on, the permeability decreases in time with little changes. The independence of system permeability from hydraulic gradient and time shows that no further blinding develops during testing after developing the equilibrium state. Filter cake was formed in relatively short time and system conserved its state while hydraulic gradients increase.

When comparing the experiments T2 and T3, it is clearly seen that the equivalent system permeability has very similar behavior over time. The experiment T3 which has two layers of TS40 nonwoven geotextile, however, has lower permeability values. At the end of the test, system permeability of T2 is about $0.06\text{--}0.07 \times 10^{-8}$ m/s, on the other hand, the system permeability of T3 is 0.04×10^{-8} m/s.

Also, in the experiment T3, the time to reach steady state after formation of filter cake (i.e. after $i=2.5$) is less than experiment T2. It can be observed that, equivalent system permeability can be decreased by having a greater constriction number, which is provided by using two layers of nonwoven geotextile. On the other hand, the time required to form the filter bridge in the soil is not related with used geotextile, it is directly related with soil itself.

For all the cases, it was observed that while GR decreased, the permeability of the soil decreased. Therefore, there were no continuous piping phenomenon, i.e. decreasing GR and increasing system permeability.

Temporal variations in the permeability at different depths in the soil section of permeameter have been shown in Figure 3.14.



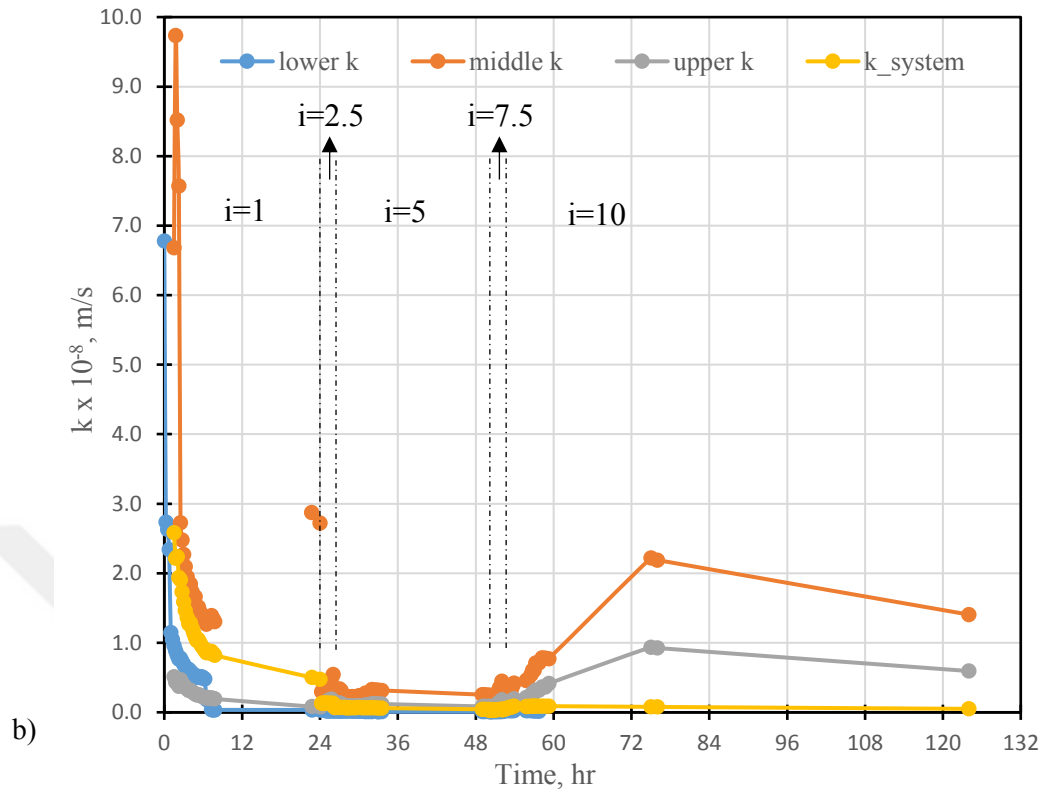


Figure 3.14 Temporal characteristics of permeability at three different depths in the soil specimen, for experiment a) T2 and b) T3

In the graphs (Figure 3.14), the “upper” term represents the layer that in the soil section of the permeameter between the soil surface to Port 4, “middle” is the layer in between Port 4 and Port 6, which is the mid-section of the permeameter. “Lower” term refers to the soil-geotextile interface zone which is layer in between Port 6 to bottom of the soil specimen (Figure 3.15).

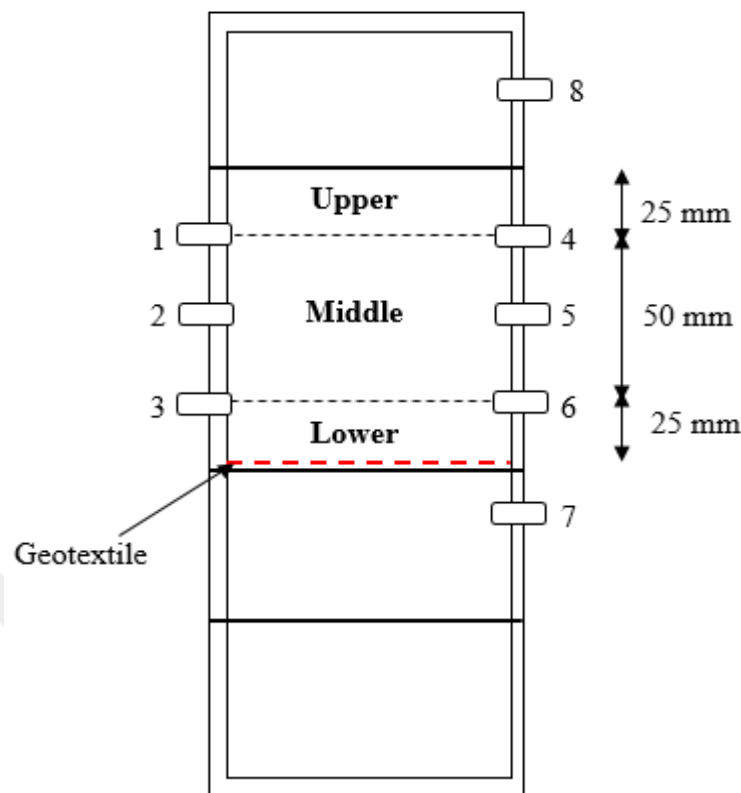


Figure 3.15 The scheme of the upper-middle-lower layer of permeameter

For both of the experiments T2 and T3, soil permeability of the upper layer had always greater value, and also significant fluctuation in values was observed. It may be because of heterogeneity of the particles in the upper layer, which might have occurred during the placement of the specimen, i.e. during the compaction phase of the specimen.

In the time between 48 hours to 72 hours, i.e. at $i=7.5$, the permeability of upper and middle layer increased slightly. This might be caused due to migration of fine particles through to lower layer with flow. Fluctuations in the permeability values were caused due to having a higher level of fines contents in the specimen.

The permeability of soil in the lower layer was always less than the middle and upper layers for both of the experiments T2 and T3. This showed that, the less permeable filter cake is formed just above the geotextile.

The permeability of lower layer decreases at the hydraulic gradient of 1. It might be due to blocking or blinding of fine particles through the geotextile. The filter cake was formed after $i=1$, and it prevented blinding process for the higher hydraulic gradient. Therefore, the permeability in the lower layer remained stable.

The system permeability behavior was similar to the permeability of lower level almost for all hydraulic gradients. This indicates that system shows the behavior of the soil layer adjusted to geotextile. To understand the scenario of the formation of filter cake and the attitude of the system permeability, tests can be conducted with a permeameter cell with the distance between geotextile and the port that just above it can be decreased.

In Table 3.6, the stabilized GR and K_R values are summarized. A review of the data shows that, the geotextile used for all cases would be considered clogged based on the criterion of GR being 1.0 or lower, as stated in ASTM D5101. On the other hand, analysis of K_R ratios showed that there would be no clogging in the system during the testing since the ratios are lower than 3.

As mentioned before, GR does not have a strict limit on their value, and it can be controlled according to the application area. So, the clogging of the geotextile should not be limited with these ratios.

Table 3.6 Stabilized GR and K_R values at the end of the tests

Experiment	Stabilized Gradient Ratio, GR	Stabilized Permeability Ratio, K_R
T1	2.56	0.37
T2	3.86	0.26
T3	3.94	0.25

Gradient ratio test also gives significant information about the clogging potential and retention performance of geotextile. At the end of each test series, the soil particles that had passed through the geotextile were collected in the bottom unit of the permeameter, and weighed after they are dried. Also, the mass of the geotextile was measured before and after testing. Then, the mass of the soil retained on the geotextile was calculated.

The mass of soil particles retained on and passing through geotextile were used to represent the percentage of migrating soil particles relative to total dry mass of soil sample used in the permeameter. In Table 3.7, the amount of particles, in grams, percentage of the piped and retained particles on geotextile, and the piping rate of system are summarized.

Table 3.7 Retained and piped soil in geotextile

Experiment	Percentage of the piped particles, i.e. particles/dry mass of specimen , %	Percentage of the retained particles, i.e. particles/dry mass of specimen, %	Piping rate, g/m ²
T1	0.11	0.07	125
T2	0.07	0.08	92
T3	0.03	0.08	37

When the percentage of retained particles on the geotextile are compared with each other, there were not major differences between the three experiments T1, T2 and T3. This shows that geotextile's ability of holding particles in it, is not affected by density state of specimen, and number of layers of geotextile. On the other hand, the percentage of the piped particles decreased with increase in density.

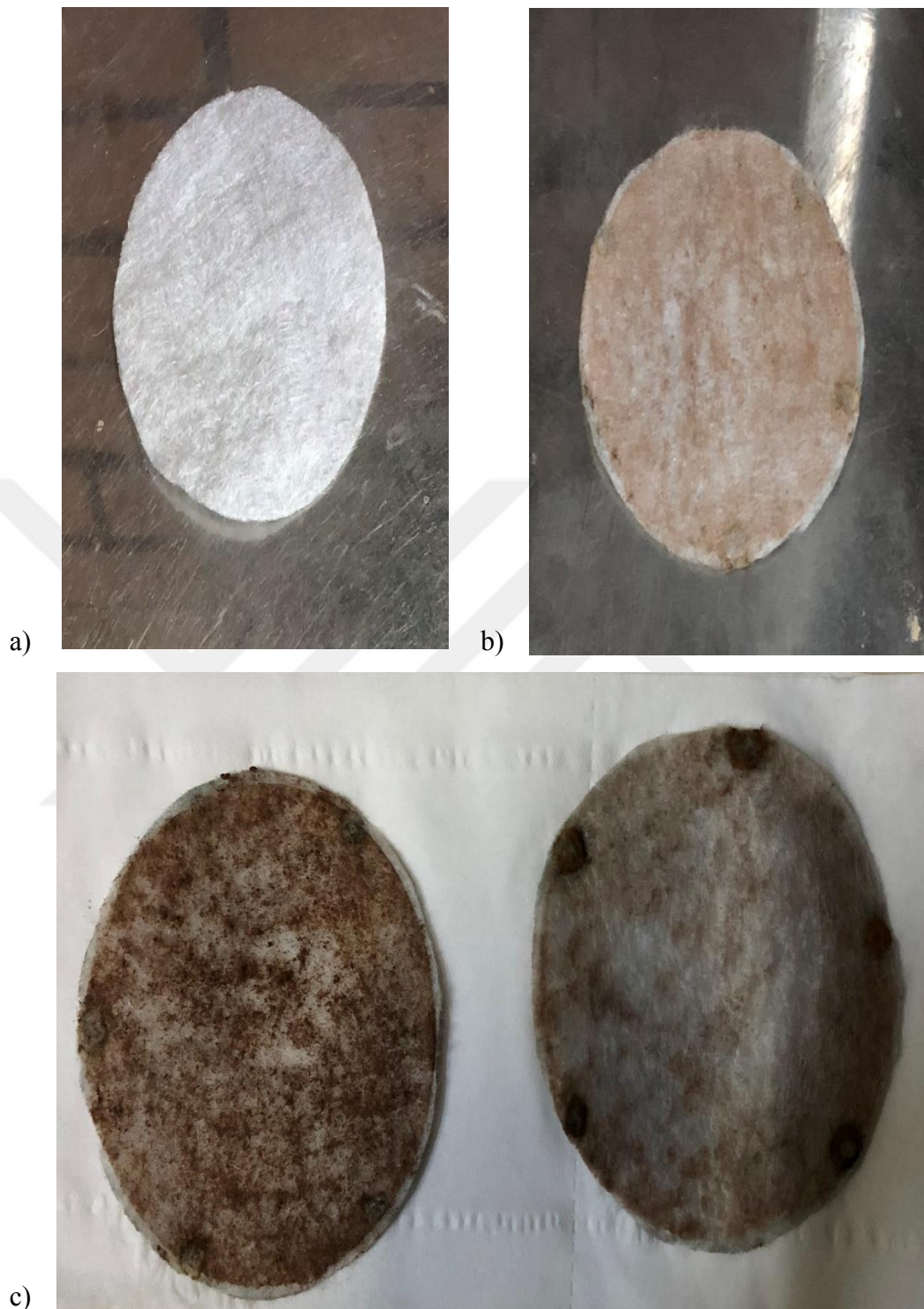


Figure 3.16 The photos of geotextile a) before the experiment T2, b) after the experiment T2, and c) after the experiment T3

Some photos of geotextile taken before and after the testing is shown in Figure 3.16. The percentage of the piped particles had the lowest value in experiment T3, which was the test with two layers of geotextile. So, using double layer of geotextile decreased the piping behavior of system.

The amount of soil piped through the geotextiles in all tests was in the range of 30-125 g/m², which was significantly lower than the limit suggested by Lafleur et al. (1989). The limit for the piping rate was stated as 2500 g/m² for the granular and geotextile filter (Jean Lafleur et al., 1989).

Having lower piping rate showed that the formation of filter cake at the soil geotextile interface contributed to retention performance of geotextile in positive way. Also, it shows that the compaction is an important factor for the gradient ratio testing in case of use of soil having fine particles. Using two layers of geotextile significantly decreases the piping rate. This might be caused by having more constriction number with using two layers of geotextile.

3.5.2 Experiments with Using Type PP3000 Nonwoven Geotextile

In T4 and T5, PP3000 type geotextile which has larger mass per unit area as compared to the geotextile in tests T1, T2 and T3 was used. Change in gradient ratio in time for both of the experiments T4 and T5 has been shown in Figure 3.17.

As seen in Figure 3.17 the GR value at the final stage of the testing, i.e. at the hydraulic gradient of 10, was smaller than 3.0. For the experiment T4, the GR value changed in the range of 0.25 to 3. Although the GR value had bigger jump at the hydraulic gradient of 2.5 and 7.5, with time passing values back to the limit of 3.0.

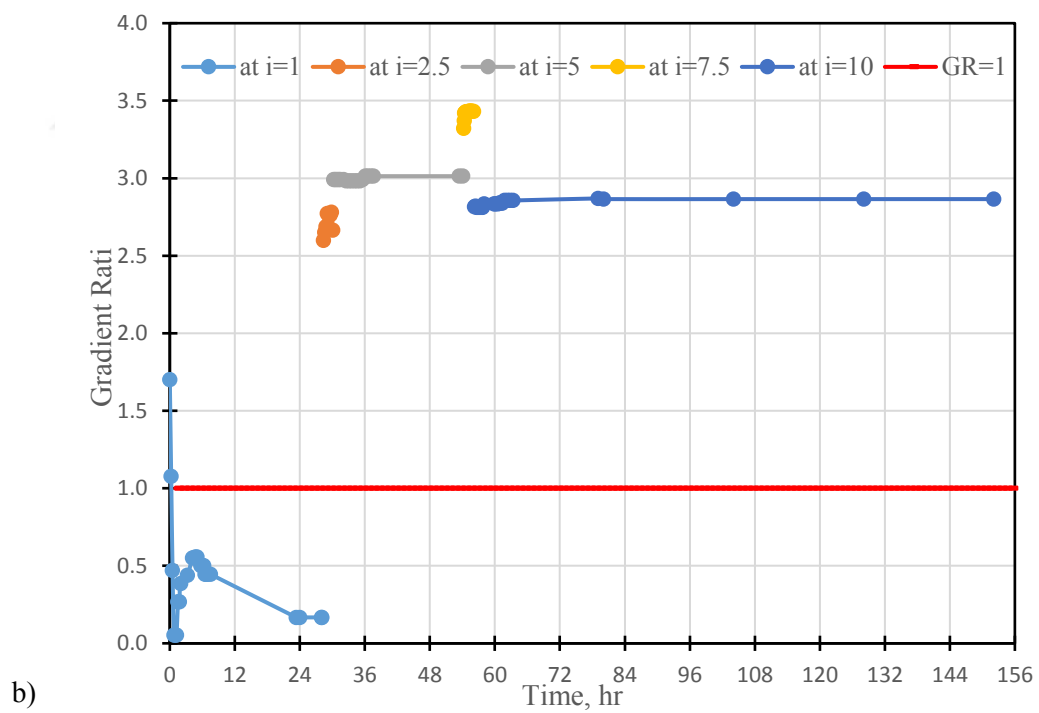
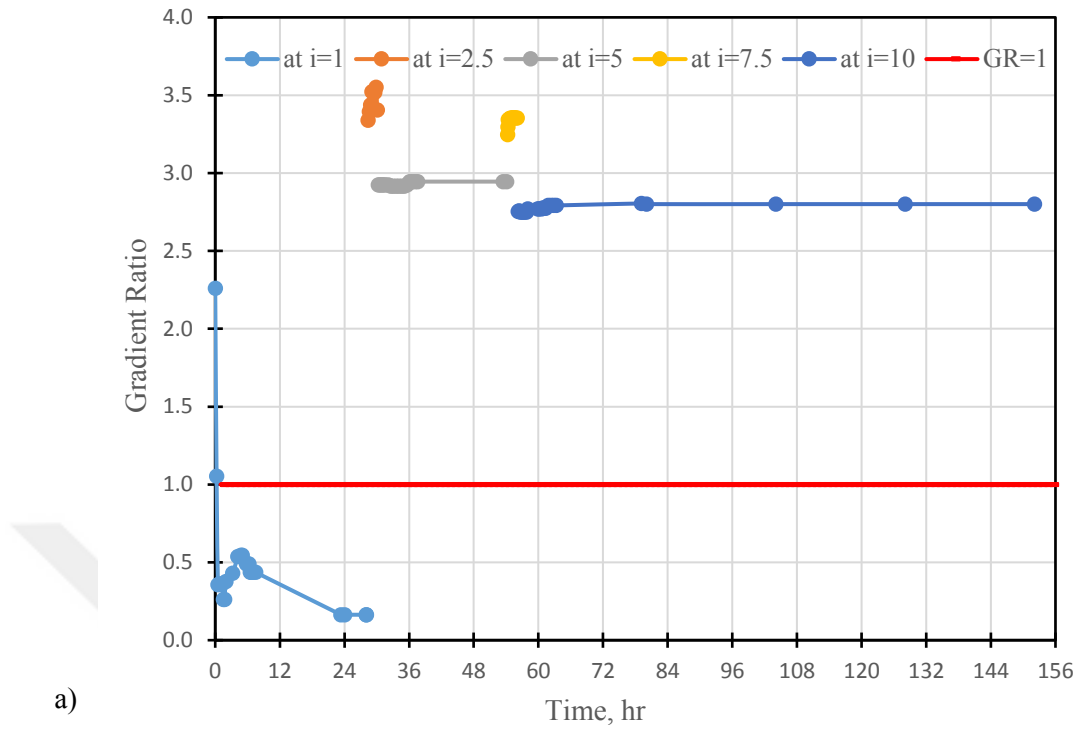


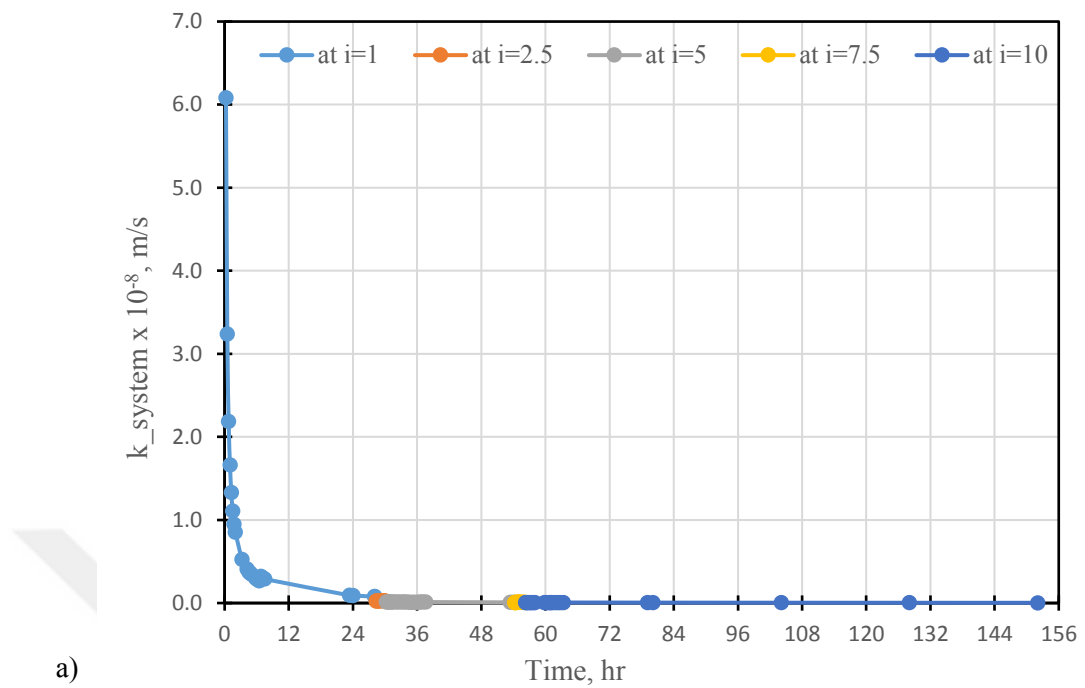
Figure 3.17 Temporal characteristics of gradient ratio with time, for experiment a) T4 and b) T5

In general, GR values showed more stable behavior at higher hydraulic gradient for both cases. Like in the experiments T2 and T3, gradient ratio was lower than 1.0 at the beginning of the testing. So, migration of the particles and rearrangement was observed at this stage of the experiment. After the hydraulic gradient of 2.5, value of GR showed small changes and it was about 3.0. It indicates that filter cake was formed at the hydraulic gradient of 1.0.

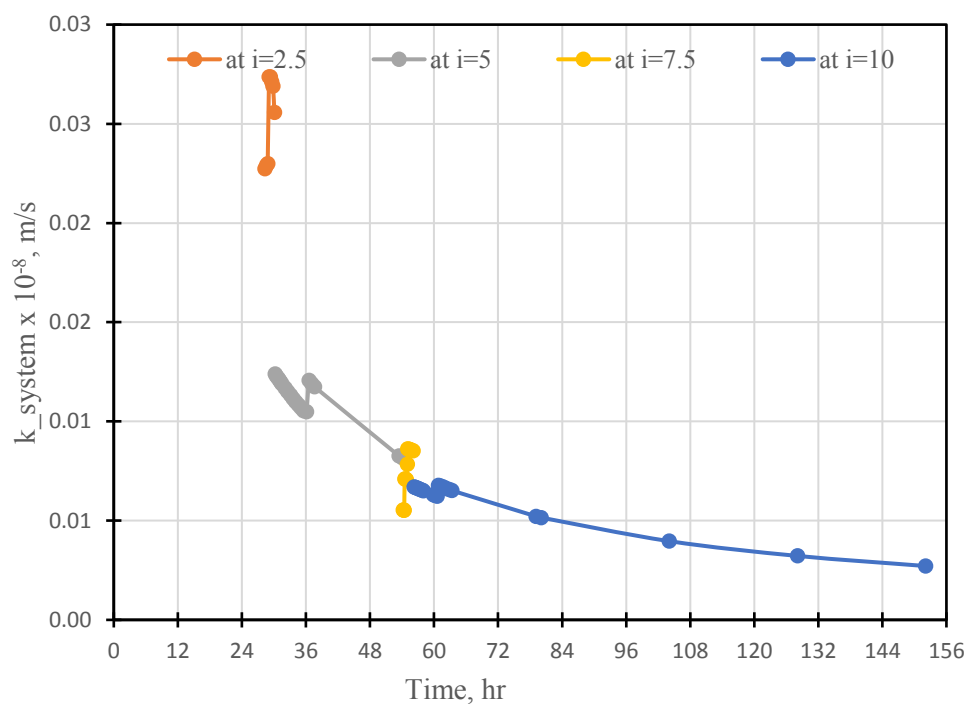
While hydraulic gradient is increased, GR values also increased and piping in the system was analyzed. For both of the experiments T4 and T5, the gradient ratio reached its maximum value after hydraulic gradient of 2.5, and there occurred no significant decreasing with time. It can be said that there were almost no change with time and with increasing in hydraulic gradient after hydraulic gradient of 2.5.

In general, the gradient ratio was greater than 1, which is defined in ASTM D5101 as a limit state. However, the gradient ratio was smaller than 3, which is also stated according to US Army Corps of Engineers' limit (Haliburton and Wood, 1982). None of them exceeds the limit of 3. So, clogging of the geotextiles was not observed during testing.

Figure 3.18 presents that change in permeability of soil-geotextile system for the experiments T4.



a)



b)

Figure 3.18 Temporal characteristics of system permeability with time for experiment T4 a) all hydraulic gradients, and b) $i=2.5, 5, 7.5$ and 10

The equivalent system permeability of experiment T4 have been shown in two parts. In the first graph (Figure 3.18-a), equivalent system permeability for all of the hydraulic gradients can be seen. Permeability started with such a high value like 6×10^{-8} m/s, then it decreased with time passing. A significant decrease was observed at the hydraulic gradient of 1.0, which is similar behavior of gradient ratio. During this period, migration and rearrangement of the particles might be completed mostly.

In the second graph, Figure 3.18-b, system permeability for hydraulic gradients of 2.5, 5, 7.5 and 10 have been shown. While analyzing the second part of the graph, some jump of the permeability values was observed as expected while hydraulic gradient increased. However, it decreased again with time passing, and achieving steady state conditions.

The permeability of system showed conservative behavior, which it kept the steady state condition with little changes during testing. This was like natural soil permeability behavior. The independence of system permeability from hydraulic gradient and time shows that no further blinding develops during testing after developing the equilibrium state. Filter cake might be formed during hydraulic gradient of 1.0, and system conserved its state while increasing hydraulic gradients.

The system permeability of experiment T5 have been shown in Figure 3.19. It is also shown in two parts. In the first graph, system permeability for all of the hydraulic gradients can be seen. Permeability started at 6.5×10^{-8} m/s, then it decreased with time passing.

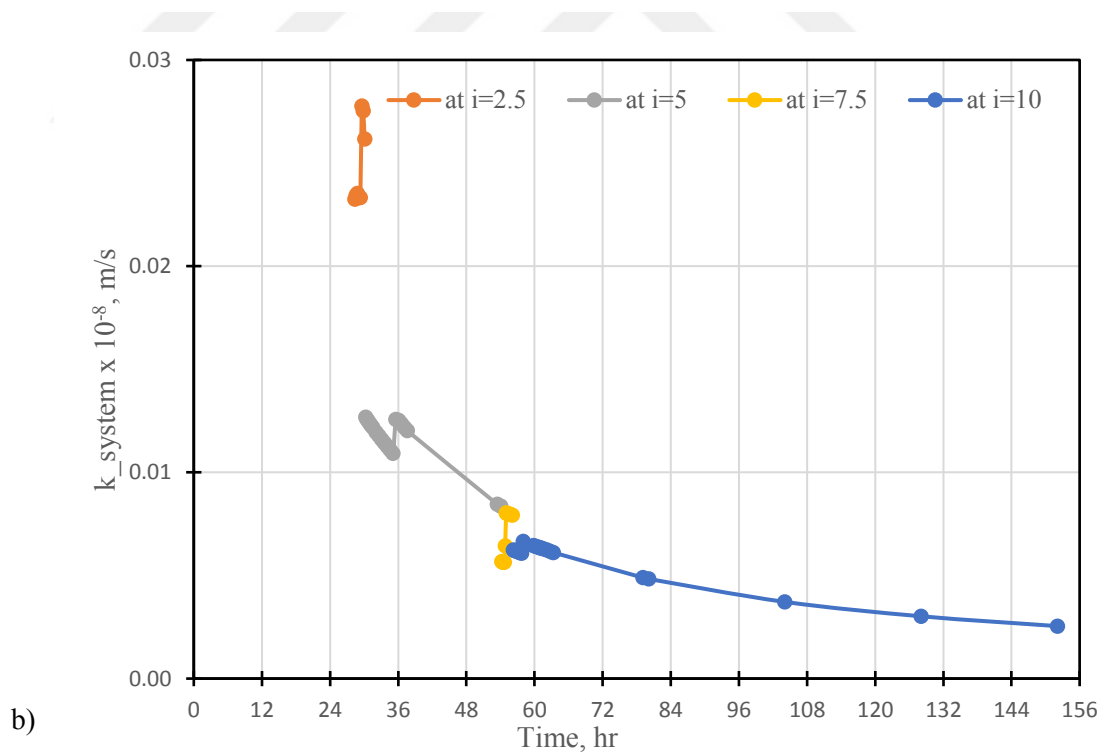
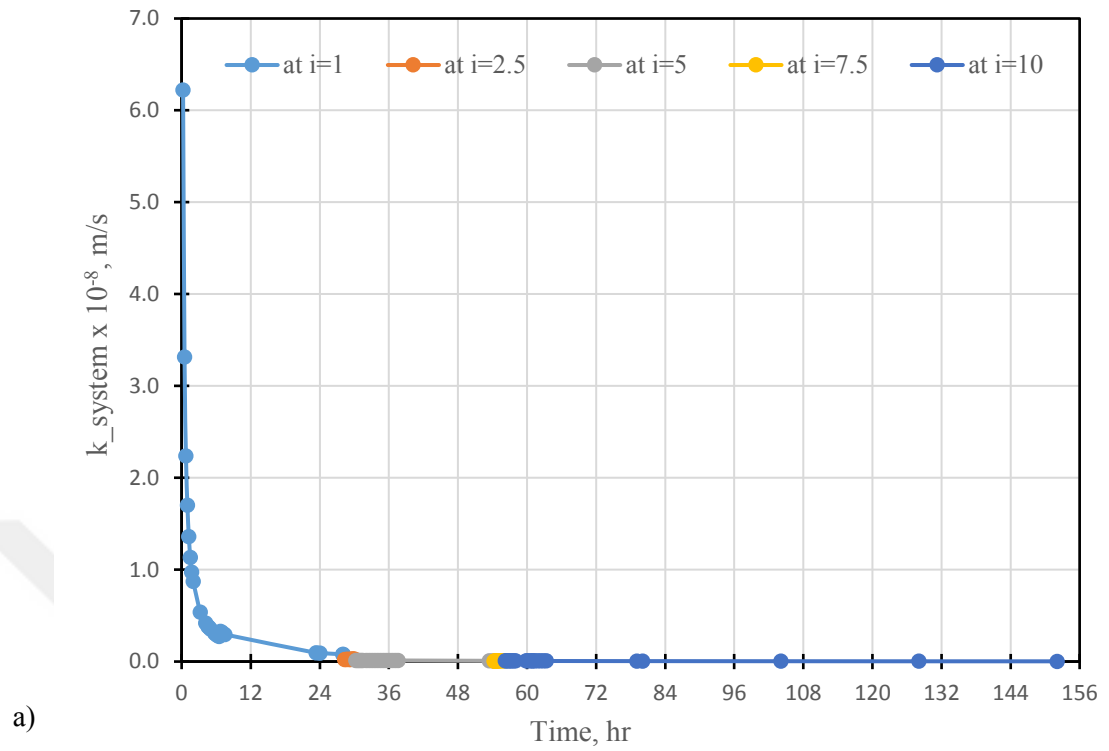


Figure 3.19 Temporal characteristics of system permeability with time for experiment T5 a) all hydraulic gradients, and b) $i=2.5, 5, 7.5$ and 10

At hydraulic gradient of 1.0, decreasing in system permeability was observed with time passing. After $i=2.5$, a small change in system permeability in the system permeability was obtained. The filter cake formation started in the hydraulic gradient of 1.0, and it was completed in this time period. At the end of the testing, the permeability of system was less than 0.01×10^{-8} m/s.

When comparing the experiments T4 and T5, it is clearly seen that the system permeability has very similar behavior. For the experiment T5, which has two layers of PP3000 nonwoven geotextile, however, lower permeability values are obtained. Also, in the experiment T5, the time to reach steady state after formation of filter cake (i.e. after $i=2.5$) is less than experiment T4.

Analyzing the experiments T4 and T5 showed that providing more constriction number with using two layers of geotextile might decrease the system permeability in general. It is also observed that the needed time to form the filter cake in soil is mostly related with soil itself as stated by Giroud (2005).

GR and the system permeability behavior showed expected behavior. It did not show piping phenomena with in increasing in decreasing in GR and increasing in permeability. So, this implies that the testing time stated in specification is suitable for the case of compacted soil and nonwoven geotextile system. Also, clogging situation is not observed during testing.

To understand better the behavior of soil layers in terms of permeability, soil was analyzed according to port distance on the permeameter. Figure 3.20 and Figure 3.21 show that the temporal variations in the permeability at different depths in the soil section of permeameter. The Figure 3.20 and Figure 3.21 show the variations for the experiment T4 and T5, respectively.

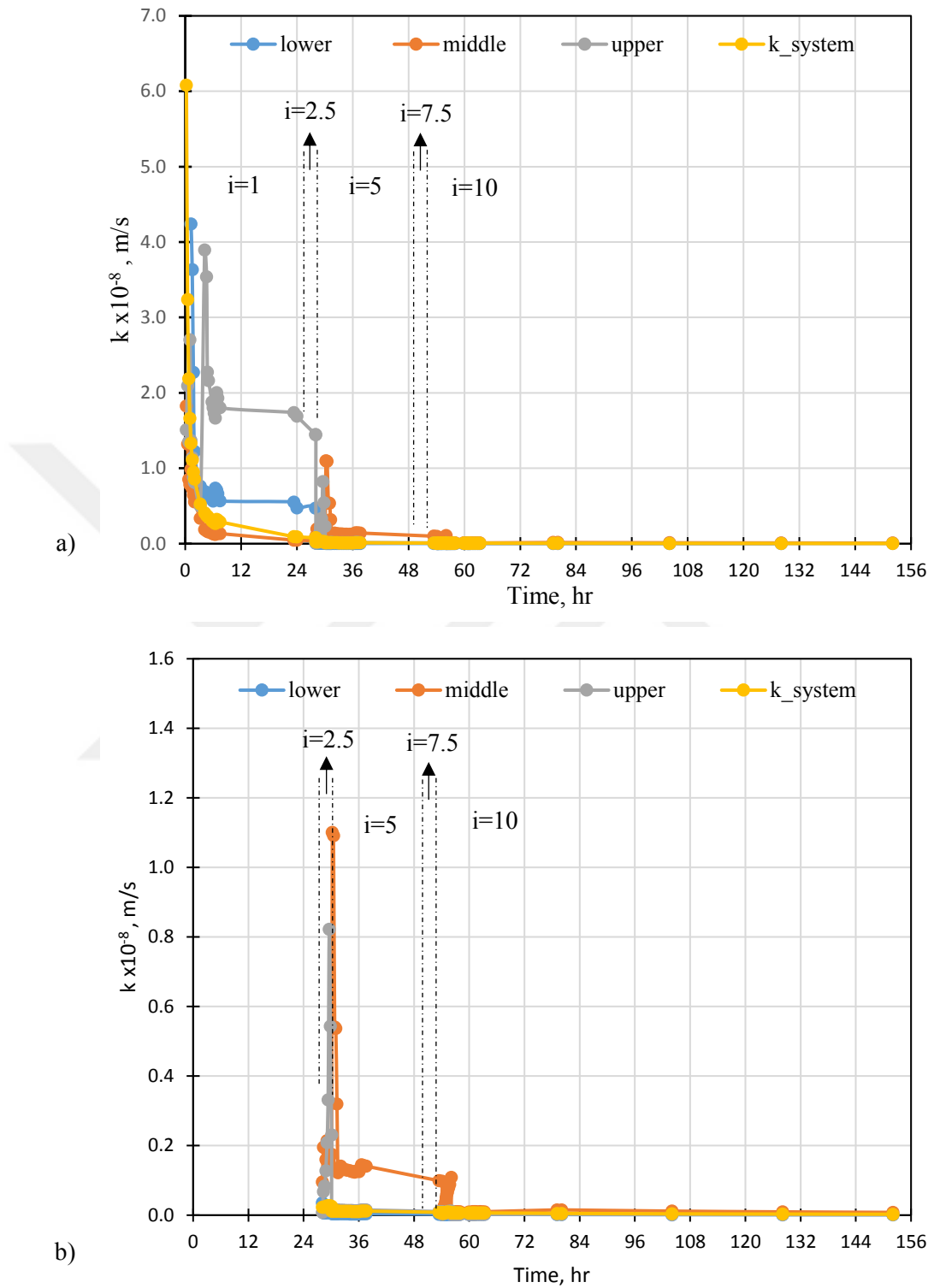


Figure 3.20 Temporal characteristics of permeability at three different depths in the soil specimen for experiment T4 a) all hydraulic gradients, and b) $i=2.5, 5, 7.5$ and 10

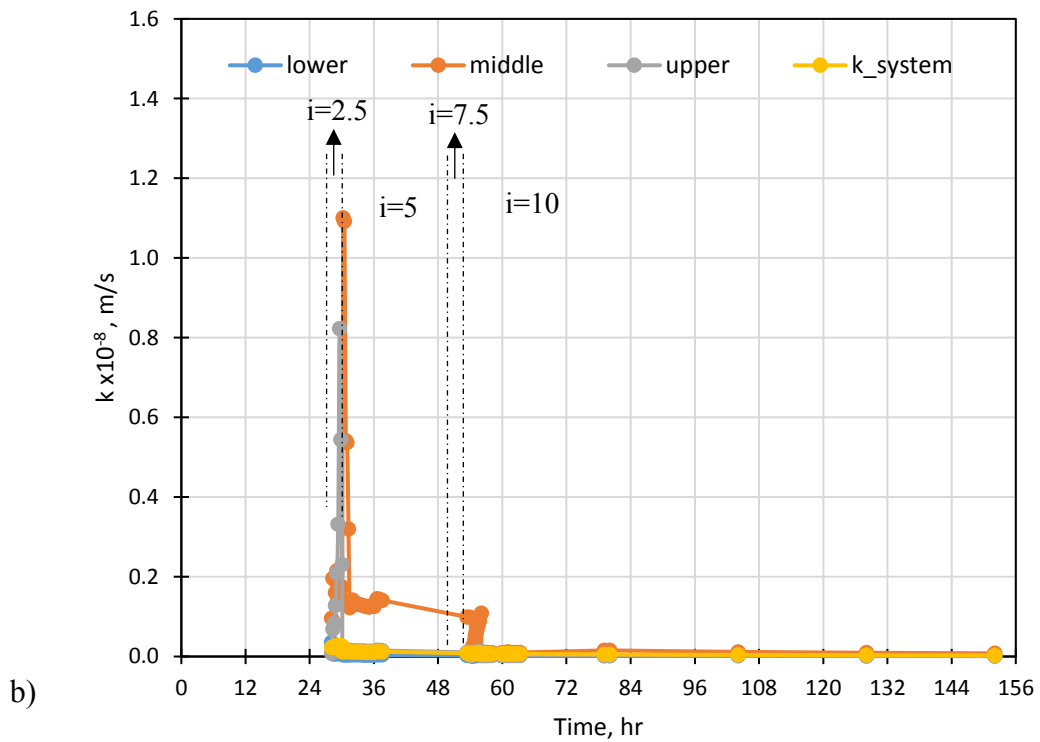
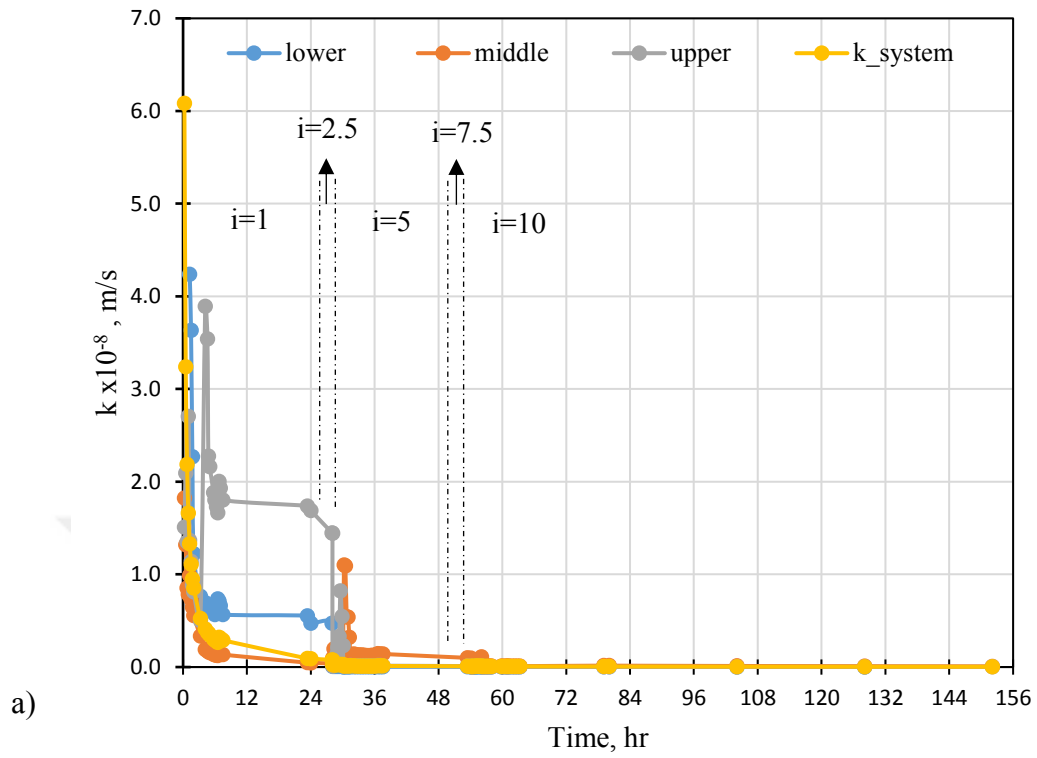


Figure 3.21 Temporal characteristics of permeability at three different depths in the soil specimen for experiment T5 a) all hydraulic gradients, and b) $i=2.5$, 5, 7.5 and 10

In the graphs, the upper, lower and middle sections have been defined earlier in this chapter (see Figure 3.15).

The detailed plot is provided for both of the experiments T4 and T5 in Figure 3.20-b and Figure 3.21-b for the hydraulic gradients of 2.5, 5, 7.5 and 10. As seen in graphs, for the interval of $i=1$ the permeability values can be comparative to each other. The permeability of middle layer had smaller value according to other layers and system. This might be due to not observed filter cake in lower layer, and some migration in particles in upper layer.

On the other hand, after $i=1$, permeability of upper and lower sections had almost same value, they did not show inconsistent behavior after reaching steady state. In detail, the permeability of soil in the lower layer less than the middle and upper layers for both of the experiments T4 and T5. This showed that the less permeable filter cake formed just above the geotextile, and the permeability of lower layer stabilized with the filter cake formation. After $i=1$, the filter cake was formed, and it prevented blinding process for the higher hydraulic gradient.

Middle layer of the soil had greater value according to upper and lower layers, for the case of $i=2.5$ and $i=5$, i.e. the time period in between 24 to 50 hours. This might show that migration of soil and particle arrangement still continued in the middle layer in this time period. This can be caused due to placement of soil in the beginning of testing. Another effect can be formation of filter cake adjacent to geotextile affects the permeability of middle layer.

The system permeability behavior was very close to the permeability of lower layer, especially after the hydraulic gradient of 2.5. It shows that the system had similar behavior with the soil layer adjusted the geotextile for both of the experiments T4 and T5. The filter cake formation affects permeability of the system. In the lower layer, it is better to use ports with less distance in between. It helps to examine the behavior of filter cake formation and its effects on system permeability.

Table 3.8 Stabilized GR and K_R values at the end of the tests

Experiment	Stabilized Gradient Ratio, GR	Stabilized Permeability Ratio, K_R
T4	2.80	0.36
T5	2.87	0.35

The stabilized value for GR and K_R have been shown in Table 3.8. According to ASTM D5101 GR criterion, i.e. $GR=1$, used geotextiles would be considered clogged for both of the experiments T4 and T5. However, as stated in ASTM D5101, the gradient ratio should be specified with site project based. Therefore, since any permeability or flow problem did not observe during the experiments, the used geotextiles were suitable for filtration mechanism for Kayseri clay.

On the other hand, the limit state for gradient ratio was described as 3 according to US Army Corps of Engineers' limit (Haliburton and Wood, 1982). Both of the test results of GR smaller than the limit of 3. So, it can be said that clogging of geotextiles did not observed during testing.

The permeability ratio was also smaller than 3, which is stated as a ratio limit for K_R (Kutay & Aydilek, 2005). According to ratio of permeability, there would be no clogging in the system during the testing.

ASTM D5101 gradient ratio test states that collecting the passed soil particles through the used geotextile gives idea for properties of geotextile in terms of filtration and clogging potential. The collected soil particles in the bottom unit of permeameter were weighed at the end of each test series. Besides that, the mass of the used geotextiles was measured before and after testing for the experiments T4 and T5. Retained soil particles on the geotextiles were calculated by this process.

Table 3.9 shows that the amount of particles, in g, percentage of the piped and retained particles on geotextile, and the piping rate of system.

Table 3.9 Retained and piped soil in geotextile (for the experiments T4 and T5)

Experiment	Percentage of the piped particles, i.e. particles/dry mass of specimen, %	Percentage of the retained particles, i.e. particles/dry mass of specimen, %	Piping rate, g/m ²
T4	0.05	0.03	63
T5	0.03	0.04	35

The percentage of the piped and retained particles, also, the piping rate were very close for both experiments. There were no main difference when comparing collected and retained particles mass for experiments T4 and T5. However, the use of two layers geotextile in the system (test T5) shows that both the qualitative and quantitative performance of geotextile became considerably good. During the experiment T5, the water collected in the bottom permeameter was relatively more clean and clear. Also, obtained piping rate and percentage values support this argument.

The amount of soil piped through the geotextiles in both tests T4 and T5 did not exceed 65 g/m². The obtained value for piping rate was significantly lower than the limit suggested by Lafleur et al. (1989), which is 2500 g/m² for the granular and geotextile filter (Jean Lafleur et al., 1989).

Some photos of geotextile PP3000 taken before and after the testing is shown in Figure 3.22.



Figure 3.22 The photos of geotextile a) before the experiment T4, b) after the experiment T4, and c) after the experiment T5

In the experiment T5, the filter cake was obtained in lesser time and the system permeability reached equilibrium in shorter time. Having smaller piping rate and filter cake formation in the experiment T5 showed that piping rate is affected by filter cake formation. Having more stable and good filter cake decreases the piping rate. This might be caused by having more constriction number with using two layers of geotextile.

Some of the experiments were performed for periods exceeding 24 hours for the hydraulic gradient of 10, and the long term performance of the test series was evaluated. It was observed that once the system reached in equilibrium in terms of flow the gradient ratio values and the permeability of soil and system did not change with time. It can be concluded as, the test period of 24 hours as stated in ASTM D5101 is sufficient to evaluate the filtration behavior and clogging potential of the saturated compacted clays.

3.5.3 Experiment with Using Granular Filter Mixture

In the final experiment of T6, which was conducted with granular filter material, the flow behavior of system was analyzed. The granular filter mixture was placed in the two permeameter at the bottom then Kayseri clay was placed on them. The Figure 3.23 shows the placement of granular filter and clay in permeameter of test set-up.

For the experiment T6, the wire mesh was removed from the permeameter cell system to place granular filter mixture in the 1st and 2nd permeameter cells. The 1st and 2nd permeameter cells were full of with granular filter material, and 3rd cell contained with well-compacted Kayseri clay. All procedures was applied same as other 5 experiments conducted with using geotextile.



Figure 3.23 The permeameter set-up for the experiment T6

According to obtained data, the flow in the granular filter-soil system generally showed stable pattern in the beginning of the test. Flow path increased with changing hydraulic gradient. Figure 3.24 shows that the flow of water for the granular filter experiment.

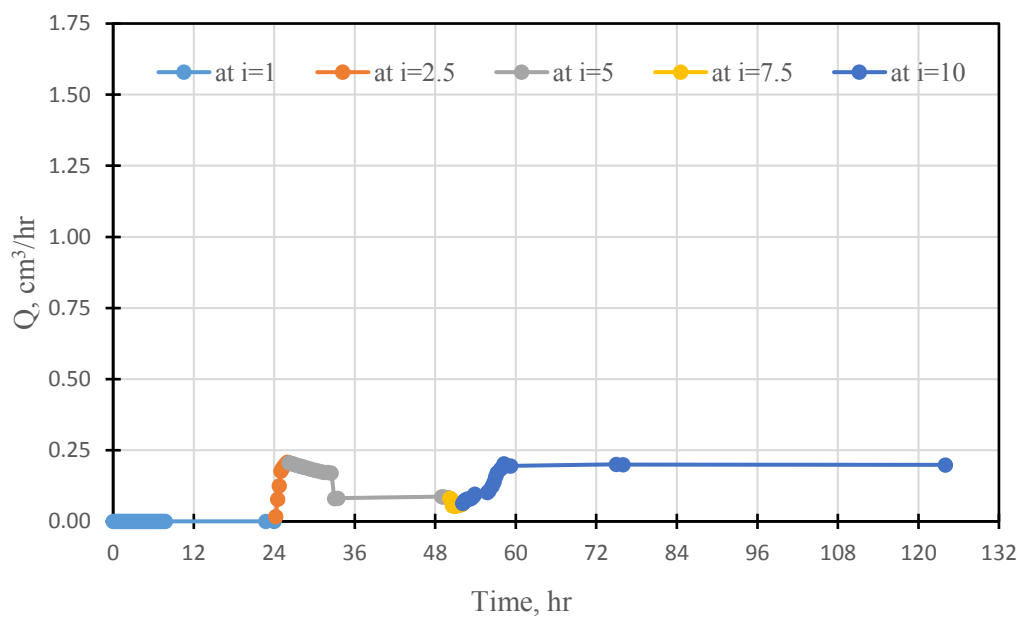


Figure 3.24 Flow of water for the experiment T6

As seen in Figure 3.24 flow rate of water was very low in the beginning of the testing. When hydraulic gradient of system was increased, flow rate also increased. Generally, flow rate changed in the range of 0.02 to 0.20 cm³/hr.

Flow rate reached in equilibrium after some jumping at change in hydraulic gradient. This shows that filtration mechanism and filter cake was formed in early stage of testing.

In Figure 3.25, flow rate results obtained from three experiments, which are granular filter-soil system (experiment T6), two-layer of TS40 geotextile-soil system (experiment T3), and two-layer of PP3000 geotextile-soil system (experiment T5) have been shown. For comparison, two-layer geotextile system was selected because of their better performance according to using one-layer geotextile in the test set-up.

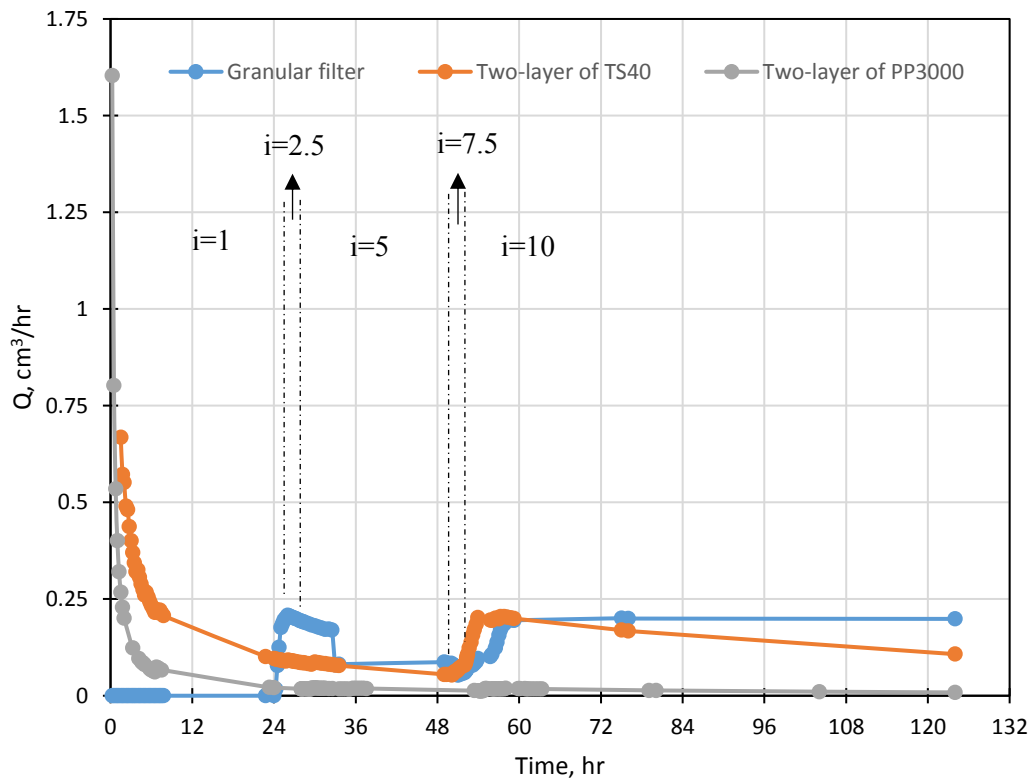


Figure 3.25 Flow rate of the experiments that are granular filter-soil system, two-layer of TS40 geotextile-soil system and two-layer of PP3000 geotextile

In the experiments conducted with geotextiles, flow begun in the early stage of testing. On the other hand, flow did not observed during $i=1$ for the filter material-soil system case.

The two-layer of TS40 geotextile-soil system showed almost similar behavior with granular filter-soil system in the testing. Both of them had small jumping at the hydraulic gradient changes and achieved the stable flow regime with time passing. It shows that blinding or piping was not observed during experiments.

On the other hand, two-layer of PP3000 geotextile-soil system had more stable flow rate. It had the most lower flow rate among other experiments, and it was more stable despite time passing.

Having smaller opening size (AOS of 0.077 mm), like the type of PP3000 geotextile, provides lesser time to reach both stable flow rate and permeability of system. The type of PP3000 geotextile had more retained particles on it, which was a benefit for filter material used in earth dams. For the case of earth dam design, filter material is designed to be a bit clogged because of preventing excessive flow of water.

At the end of the experiment T6, the permeameter units contained granular filter mixture weighed and sieve analysis had been completed (see Figure 3.26). The amount of migrated particle and piping rate of granular filter-soil test system had been analyzed. As seen in the Figure 3.26, curve shifted to up, which indicates that the amount of finer particles was increased because of migration in clay soil cell towards to granular filter.

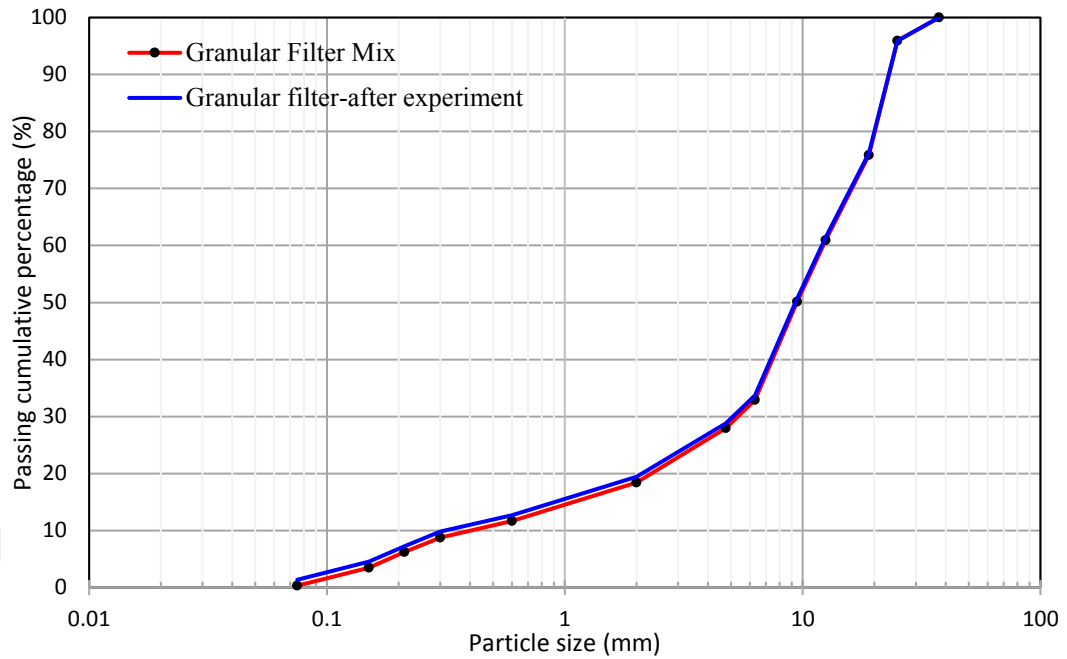


Figure 3.26 Grain size distribution curve of the granular filter mixture after the experiment

The migration of particles also had affected the test set-up condition. Flow was in the direction of vertical, and this forced the particles to migrate through the granular filter. Formation of filter cake was completed in the hydraulic gradient of 2.5. Then, flow continued in conservative path.

The permeameter units contained granular filter mixture weighed and both the sieve analysis of granular filter mixture before and after experiment had been compared. The percentage of migrated particle and piping rate of granular filter-soil test system had been analyzed. According to obtained data, percentage of piped particles was 1.37 %, and corresponding piping rate was 2270 g/m².

The percentage of piped particles was higher than all the geotextile-soil system experiments' results. Moreover, the piping rate was lower than the limit value suggested by Lafleur et al. (1989), which is 2500 g/m² for the granular and geotextile filter (Jean Lafleur et al., 1989).

In general, when comparing the duration of achieving steady state for all testing, following data were obtained (see Table 3.10).

Table 3.10 Required time to achieve steady state condition

Experiment	Used Geotextile	Passing time for steady state condition
T1	1 Layer of TS40	-
T2	1 Layer of TS40	31 hr
T3	2 Layer of TS40	29.5 hr
T4	1 Layer of PP3000	29.5 hr
T5	2 Layer of PP3000	27 hr
T6	Granular Filter	26.5 hr

The passing time to achieve steady state condition of permeability is directly related with formation of filter cake. According to study conducted by Aydilek (1991), the normal behavior was defined as decreasing in hydraulic conductivity of system with time until it reaches a constant value due to the formation of a filter cake on the geotextile. Therefore, the passing time to reach constant value for hydraulic conductivity of system is the time for filter cake formation.

It is clearly seen from Table 3.10 that, using two-layer geotextile reduced the needed time to have stable permeability and flow in the soil-geotextile system. As it is defined earlier, having more constriction number with using two-layer of geotextile affects the filtration performance of the system in positive way. It reduced the needed time for steady state permeability conditions, reduced the piped particles amount and piping rate of system.

Since the density state of experiment T1 was loose in accordance with other experiments, the stable condition for permeability of system was not achieved in the desired duration of testing, i.e. in 24 hours defined in the specification ASTM D5101.

For the experiments conducted with type TS40 geotextile, both of the experiments T2 and T3 had greater duration for steady state than the experiment with granular filter. Also, their piping rate was slightly higher than the other experiments (see

Table 3.7 and Table 3.9). However, using two-layer of geotextile made considerable difference. It reduced the time needed to reach to steady condition for hydraulic conductivity and piping rate was affected in positively.

The experiment T4 and T5, which were conducted with type PP3000 geotextile, showed similar performance with granular filter-soil system testing. In the experiment T5, the duration for steady state of hydraulic conductivity was lesser than the experiment T4, and very close to granular filter-soil system testing. So, it can be observed from the study that having smaller apparent opening size is more compatible with fine grained soils like Kayseri clay used in this research.

All the data collected during the experiments have been provided in the Appendices part of this thesis.



CHAPTER 4

CONCLUSIONS

4.1 Summary

Designing proper filters in earth dams can prevent many damages before it happens. Excessive soil movement from dam body, i.e. piping in the soil media, results with greater seepage. This situation leads to soil erosion in the dam. Therefore, selection of proper filter material, and designin it properly is a keypoint of filter mechanism.

Two main points that should satisfied by filter in any construction are permeability and retention criteria. The filter should have large openings to satisfy permeability criterion, and it should have sufficiently small openings not to allow particles to pass, so, satisfy retention criterion.

Beside the granular filters which are commonly used as a filter material in dams, geotextiles might be considered as the best option for filtration. The geotextiles are mostly used in the parts of dams such as chimney drains, trench drains, blanket drains and heel drains. Also, using geotextile as a filter material can contribute protecting the environment and natural resources, provide sustainability of construction materials, reducing the carbon footprint of the project and reduction of cost.

In recent years, having difficulties in finding proper granular filter material has caused to look for alternative filter materials in Turkey and as well as around the world. Even if sufficient amount of granular filter can be obtained, transportation of materials to the construction site is becoming more difficult and it is directly affecting the cost of the project negatively. On the other hand, carbon footprint of the project can raise when using granular filter. Furthermore, production of clean granular materials from rock quarries cause disturbance to the natural resources.

All in all, use of geotextiles as a filter material is becoming best option instead of granular soil.

To study currently used design criteria and usage of geotextile with clay soil which can be used in clay core of earth dam several tests were conducted and analyzed in this study. All the tests were performed according to specification of ASTM D5101. In this context, behavior of two geotextiles in accordance with their apparent opening size, thickness and mass per unit area were investigated under different hydraulic gradients. So, feasibility of non-woven geotextile used as a filter material was demonstrated with the experimental study of gradient ratio tests on soil-geotextile system for compacted clay.

With these analyses, the international standards for granular filter and geotextile filter were compared. Existing methodology for design of geotextile as a filter material had been reviewed and defined their principal criteria. The applicability of the existing design criteria for compacted clay was analyzed with interpretation of obtained data from conducted tests.

In the test system, compatibility of the soil and nonwoven geotextile in terms of the properties of gradient ratio of system, permeability of system and soil, and flow rate in the system within time were analyzed. Selected geotextiles were analyzed in terms of design criteria especially for permeability and retention criterion. At the end of the test, the particles retained on geotextile and piped through the geotextile were collected and analyzed for the total rate of piping.

4.2 Conclusions

In general, the possibility of using geotextile filters instead of granular filter next to where clay is used as a base material had been investigated, and some of the conclusions reached at the end of this study are:

- Although it is stated in the specification of ASTM D5101 that the gradient ratio should be 1.0, different values can be adopted in different projects.

The stability and uniformity in the system is more important, and there is no strict value for gradient ratio.

- Filtration characteristics are affected by degree of compaction of soil. Higher GR and K_R values are obtained for the soil with lower density. Furthermore, higher amounts of fine accumulated in the test of soil having lower density.
- Using thicker geotextile (among selected geotextiles) shows better filtration performance in terms of having lower piping rate and smaller GR and K_R value. Moreover, the time required to reach stable system permeability value is lesser than the testing system having thin geotextile.
- In the system, the permeability value increases suddenly at the very beginning of the test, then it reaches the stable position and go on till end of the testing. It shows that once the filter cake develops in the system, system permeability has a permanent value.
- In the specification of ASTM D5101 has certain limitations for testing of fine grained soil such as Kayseri clay used in this study. In ASTM D5101, 24 hours testing period is recommended. This time period is usually enough to achieve steady state for hydraulic conductivity and permeability of system in the case of compacted clay. However, the required time is more than 24 hours for the case of test with lower density. For the case of lower density, long-term tests should be performed until the stabilized gradient ratios and hydraulic conductivities are obtained.
- Study showed that the used fine grained soil can be filtered with geotextiles successfully, however, interpretation of the obtained data should be analyzed carefully. The gradient ratio, GR, cannot reflect the actual behavior of clogging for fine grained soils. On the other hand, permeability ratio, K_R which is obtained from test data gives clearer definition and better idea for clogging behavior.
- The system permeability behavior is very similar to permeability of soil that is placed next to geotextile filter. In the soil layer analysis, it is observed

that the system permeability is directly related with filter cake observation and location of geotextile in the system.

- The test results show that use of a two-layer nonwoven geotextile increases filtration performance of a soil-geotextile system. The main advantage of using two-layer nonwoven geotextile in the system is having more constriction size. Therefore, lower GR and K_R values are obtained that are directly related with filtration performance and clogging potential of soil-geotextile system.

4.3 Recommendations for Future Study

Following topics are recommended for future studies:

- For the soil permeameter test set-up, the distance of geotextile and the port just above the geotextile may be lesser to understand filter cake formation better.
- For the clayey type soil, ASTM D5567 Hydraulic Conductivity Ratio (HCR) Testing of Soil-Geotextile Systems tests can be applied to analyze more detail in behavior of compacted soil-geotextile system.
- Various clayey soils can be used to compare filtration performance of selected geotextiles.
- The test period can be longer than 24 hours that is recommended in ASTM D5101. The permeability and hydraulic conductivity of system may be analyzed in long term performance of geotextile.
- In the analysis, flow was obtained in vertical position. The testing system can be designed in horizontal or inclined position to see different approach of flow and its effects on filtration performance.
- In the testing system, combination of woven-nonwoven geotextile, nonwoven geotextile-granular filter and woven geotextile-granular filter can be used to obtain best option.

- Economical analysis can be made for large scale construction and how much cost saving can be made.
- The tests can be repeated for different compaction state of soil.





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APPENDICES

A. Collected Data During Experiments

- **Experiment T1:** 1 Layer of TS40 geotextile and Kayseri clay with the density of 1.22 g/cm³

Table A.1 Test data of the experiment T1

Time (min)	Mass of outflow container (g)	H1	H2	H3	H4	H5	H6	H7	H8
0	0	6.6	8.4	8.8	6.8	8.6	8.4	19.5	30.8
15	0	6.6	8.6	8.9	6.8	10	8.4	19.5	30.8
30	0	6.8	8.9	8.9	7.2	10.2	8.6	19.5	30.8
45	0	6.8	9.3	9.1	7.2	11	10	19.5	30.6
60	0	6.9	9.3	9.3	7	12	10	19.5	30.6
75	0	6.9	9.6	9.3	7	12	11	19.5	30.6
90	0	7	10.2	9.6	7.2	12	11.1	20.2	30.6
105	0.5	7.1	10.2	9.7	7.2	12.2	11.3	20.2	30.8
120	0.5	7.1	10.8	9.9	6.8	12.2	11.3	20.2	30.8
135	0.6	6.8	10.8	9.9	6.5	12.8	11.2	20.6	30.5
150	0.6	9.5	14	9.9	10.7	15.8	11.2	20.7	30.3
165	0.6	9.5	14	9.9	10.7	15.8	11.2	20.7	30.3
180	0.6	10	14.5	10.2	10.7	15.9	11.2	20.7	30.3
195	0.6	10	14.5	10.2	10.7	16	11.3	20.7	30.3
210	0.6	10	14.5	10.7	10.9	16	11.3	20.7	30.3
225	0.6	10.8	14.5	11	11	16	11.3	20.7	30.3
240	0.7	11	14.6	11.3	11	16.1	11.4	20.8	30.1
255	0.7	11	14.6	11.4	11	16.1	11.4	20.8	30.1
270	0.7	11.6	14.6	11.8	11	16.2	11.4	20.8	30.1
285	0.7	11.7	14.4	12.1	11	16.1	11.4	20.8	30.1
300	0.8	11.8	14.4	12.6	11.3	16.1	11.4	20.8	30.1
315	0.8	11.8	14.4	13	11.3	16	11.5	20.8	30.1
330	0.8	11.7	14	13.3	11.6	16	11.7	20.8	30.1
345	0.8	11.8	14	13.7	11.6	15.9	11.7	20.8	30.1
360	0.8	12	14	13.9	11.5	15.9	11.7	20.8	30.1
375	0.9	12.4	14	14	11.6	15.9	11.9	21	29.9
390	0.9	12.4	14	14	12	15.6	12.1	21	29.9
405	0.9	12.6	13.6	14	12.3	15.6	12.4	21	29.9
420	0.9	13.1	13.6	14.1	12.3	15.6	12.4	21	29.9

435	0.9	13.4	13.6	14.1	12.3	15.5	12.5	21	29.9
450	0.9	13.5	13.6	14	12.6	15.5	12.7	21	29.9
465	0.9	13.8	13.6	14	12.7	15.5	12.8	21	29.9
1365	1	16	13.3	9.6	16.8	11	17	21.2	29.7
1440	1	16	13.3	9.6	16.8	11	17.1	21.2	29.7
1440	1	33	27	16	28.1	21	14.5	12.3	39.3
1441	1.1	33	27	16	28.1	21	14.5	12.3	39.3
1442	1.3	33	27	16	28.1	21	14.5	12.3	39.3
1443	1.6	33	27	16.1	28.1	21	14.5	12.3	39.3
1444	1.8	33	27	16.1	28.1	21	14.5	12.3	39.3
1445	2.3	33.3	27.3	16.6	28.8	22.4	19.4	12.4	39.4
1450	3.6	33.3	27.5	16.9	28.8	23	19.4	12.4	39.4
1451	3.7	33.3	27.5	17	28.8	23	19.4	12.4	39.4
1452	3.8	33.3	27.5	17.7	28.8	23	19.4	12.4	39.4
1452	3.8	58	55	42	60	55.1	40.1	12.2	63.2
1457	14	58	55	42.3	60	55.3	41.2	12.4	63.2
1467	32	58	55.5	42.3	60.2	55.9	41.9	12.6	63.5
1472	59.5	58.2	55.5	42.3	60.1	55.7	42.2	12.8	63.5
1477	80.2	58.2	55.5	42.8	61.5	56.9	44.1	12.9	63.5
1482	99.4	58.5	56	42.8	61.4	56.9	44.1	13	63.5
1487	117.5	58.5	56	43	61.3	56.8	44.1	13	63.5
1497	160.9	58.5	56.2	43.1	61.2	56.5	44	13.6	64
1512	217.8	59	56.2	43.1	59.8	56.4	44	14.1	63.6
1527	261.9	59	56.2	43.6	59.8	56.4	44	14.4	63.6
1542	318.2	59	56.2	43.6	59.6	56.4	43.9	14.8	63.6
1557	337.1	59.4	56.2	43.6	59.6	56.4	43.9	15	63.6
1572	352	59.2	56	43.3	59.6	56.2	43.7	15	63.6
1602	367.2	59.2	56	43.3	60.3	56	43.7	15	63.4
1632	390.5	59	56	43.3	60.1	56	43.7	15	63.4
1662	402.8	59	56	43	60	56	43.7	15.2	63.4
1692	411.4	59	55.5	42.9	60	56	43.6	15.2	63.4
1722	422.1	59	55.4	42.9	60	56	43.6	15.3	63.3
1752	431.3	58.6	55.4	42.9	58.8	55.5	43.6	15.3	62
1782	442.8	58.6	55	42.9	58.8	55.4	43.6	15.4	61.9
1812	447.8	58.6	55	42.7	58.8	55.4	43.5	15.5	61.9
1842	461.6	55	54.8	42.7	58.5	55.4	43.5	15.5	61.9
1872	470.5	55	54.8	42.5	58.5	55.4	43.5	15.5	61.9
1902	483.1	54.8	54.3	42.5	58.5	55.4	43.5	15.6	61.9
1917	493.7	13.8	13.6	14	58	15.5	43	21	36
2852	506.1	16	13.3	9.6	58	11	43	21.2	36
2892	507.9	16	13.3	9.6	58	11	43	21.2	36
2892	507.9	33	27	16	28.1	21	17	11	39.3
2893	508	33	27	16	28.1	21	17	11	39.3
2894	508.2	33	27	16	28.1	21	17	11	39.3
2895	508.5	33	27	16.1	28.1	21	17	11	39.3

2896	508.7	33	27	16.1	28.1	21	17	11	39.3
2897	509.2	33.3	27.3	16.6	28.8	22.4	19.4	12.4	39.4
2902	510.5	33.3	27.5	16.9	28.8	23	19.4	12.4	39.4
2903	510.6	33.3	27.5	17	28.8	23	19.4	12.4	39.4
2904	510.7	33.3	27.5	17.7	28.8	23	19.4	12.4	39.4
2912	517.3	33.3	27.6	17.8	28.8	22.9	19.3	12.4	39
2922	518.9	33.3	27.9	18	28.8	22.8	19.7	12.5	38.8
2927	526.6	33.5	27.9	18.8	28.8	22.9	19.7	12.7	38.2
2937	528.3	33.5	28.8	19.3	29	23	19.9	12.8	38.2
2942	529.3	33.5	28.8	19.6	28.9	23	20	12.8	38
2947	529.8	33.5	28.7	20	28.9	23	19.9	13	38
2949	530.3	33.6	28.7	20.9	28.9	23	19.9	13	38
2952	531.2	33.6	28.7	20.9	28.8	22.9	19.9	13	37.8
2962	531.9	33.4	28.6	20.9	28.8	22.7	20	13.2	37.6
2967	532.2	33.4	28.6	20.9	28.8	22.7	20	13.2	37.6
2972	532.6	33.4	28.6	20.9	28.8	22.7	20	13.2	37.6
2977	533.4	33.4	28.6	20.9	28.8	22.7	20	13.4	37.3
2982	533.9	33.4	28.6	20.9	28.8	22.7	19.9	13.4	37.2
2987	534.2	33.4	28.6	20.9	28.8	22.7	19.8	13.4	37.2
2997	534.5	33.4	28.6	20.9	28.8	22.7	19.7	13.3	37.2
3002	534.8	33.4	28.6	20.9	28.8	22.7	19.7	13.3	37.1
3012	535	33.4	28.6	20.9	28.8	22.7	19.7	13.3	37.1
3012	535	79	75	57	82	73.8	62	0.5	110
3017	554.1	79	75	57.2	82	73.8	62	0.5	110
3022	600.1	79	75.5	57.2	82	73.5	62	0.5	110
3027	635.8	79	75.5	57.3	82	73.5	61.9	0.5	110
3032	673.4	79.8	75.5	57.3	81	73.1	61.9	1.0	109
3037	706	79.8	75.3	57.3	81	73.3	61.8	1.2	109
3042	735.5	79.9	75.3	57.2	80.3	73.3	61.7	1.7	108.4
3047	772.7	79.9	75.3	57.2	80.1	73.5	61.9	2.1	108.4
3052	804.5	79.9	75.3	57.2	80.1	73.4	61.9	2.3	108.1
3057	830.5	79.9	75.3	57.1	80	73.4	61.7	2.4	108
3072	918.9	79.6	75.3	57.0	79.1	73.4	61.8	2.7	106
3082	968.2	79.6	75.1	57.0	79.1	73.4	61.8	2.8	105.8
3112	1017.5	79.6	75.1	57.0	79.1	73.4	61.8	3.0	104.3
3142	1066.8	79.6	75.1	56.8	79	73.4	61.5	3.2	104.3
3172	1116.1	79.3	75.1	56.8	79	73.4	61.5	3.4	103.2
3237	1165.4	79.3	75	56.8	79	73.4	61.5	3.6	103.1
3252	1214.7	79.3	75	56.8	78.8	73.4	61.0	3.8	103
3267	1220.3	79.3	75	56.8	78.8	73.4	61.0	4.0	102.1
3282	1225.9	79	74.9	56.5	78.8	73.4	61.2	4.2	102.1
3297	1231.5	79	74.9	56.5	78.7	73.5	61.3	4.4	102
3312	1237.1	79	74.9	56.5	78.7	73.5	61.3	4.6	102
3327	1242.7	79	74.9	56.6	78.6	73.4	61.6	4.8	101.5
3342	1248.3	79	73.5	56.5	78.5	73.5	62	5.0	101.5

3357	1253.9	79	73.5	56.5	78.5	73.5	62	5.2	101.3
3372	1259.5	79	73.6	56.3	78.5	73.6	62.8	5.4	101.2
3387	1265.1	79	73.6	56.3	78.3	73.6	62.9	5.6	101.1
3402	1270.7	78.8	73.7	56.3	78.3	73.7	63.1	5.8	100
3417	1276.3	78.8	73.7	56.3	78.4	73.7	63.5	6.0	99.9
3432	1281.9	78.8	7.4	56.3	78.3	7.4	63.5	6.2	99.8
3447	1287.5	78.7	74	56.3	78.3	74	63.7	6.4	99.7
4392	1731.8	85.4	83.2	82.1	78.5	83.2	66	14.3	94
4397	1732.2	85.4	83.2	82.1	78.5	83.2	66	14.3	94
4302	1746.3	85.4	83.2	82.1	78.5	83.2	66	14.3	94
4452	1847.3	85.4	83.2	82.1	78.5	83.2	66	14.3	94

- **Experiment T2:** 1 Layer of TS40 geotextile and Kayseri clay with the density of 1.59 g/cm³

Table A.2 Test data of the experiment T2

Time (min)	Mass of outflow container (g)	H1	H2	H3	H4	H5	H6	H7	H8
0	0	14.4	21.2	14.8	14	21.6	14.5	16	25
15	0	14.4	21.2	14.8	14	21.6	14.5	16	25
30	0	14.4	21.2	14.8	14	18.3	14.5	16.3	24.7
45	0	14.4	21.1	14.8	14	19.7	14.4	16.3	24.7
60	0	14.4	21.1	14.8	14	20.1	14.8	16.3	24.7
75	0	14.4	21.1	14.8	13.9	20.1	14.8	16.3	24.7
90	1	14.3	21.1	14.6	13.9	23.6	15.6	16.4	24.7
105	1	14.3	21.1	16.5	13.7	21.2	14.7	16.4	24.7
120	1.1	14.3	21.1	14.5	13.6	21.3	14.7	16.4	24.3
135	1.1	14.3	24.3	14.4	13.6	21.3	14.7	16.4	24.5
150	1.2	14.3	24.3	12.7	16	26.7	13	16.4	24.5
165	1.2	14.3	24.3	12.7	16	26.7	13	16.4	24.5
180	1.2	14.3	24.3	12.7	16	26.7	13	16.4	24.5
195	1.2	14.3	24.3	12.7	16	26.7	13	16.4	24.5
210	1.2	14.3	24.3	12.7	16	26.7	13	16.4	24.5
225	1.2	14.3	24.3	12.7	16	26.7	13	16.4	24.5
240	1.3	14.3	24.3	12.7	16	26.7	13	16.4	24.5
255	1.3	14.3	24.3	12.7	16	26.5	13	16.4	24.5
270	1.3	14.3	24.3	12.7	16	26.5	13	16.4	24.5
285	1.3	14.3	24.1	12.7	15.8	26.5	13	16.4	24.5
300	1.3	14.3	24.1	12.5	15.8	26.5	12.8	16.4	24.5
315	1.4	14.3	24.1	12.5	15.8	26.4	12.8	16.3	24.5

330	1.4	14.2	24.1	12.5	15.8	26.4	12.8	16.3	24.5
345	1.4	14.2	24.1	12.5	15.8	26.4	12.8	16.3	24.5
360	1.4	14.2	24.1	12.5	15.7	26.4	12.8	16.3	24.4
375	1.4	14.2	24.1	12.5	15.7	26.2	12.8	16.3	24.4
390	1.4	14.2	24.1	12.5	15.7	26.2	12.8	16.3	24.4
405	1.5	14.2	24.1	12.4	15.7	26.2	12.8	16.3	24.4
420	1.5	14.2	24.1	12.4	15.5	26.2	12.8	16.3	24.4
435	1.6	14.2	24	12.4	15.5	26.2	12.8	16.3	24.4
450	1.6	14.2	24	12.4	15.5	26.2	12.8	16.3	24.4
465	1.6	14.2	24	12.4	15.5	26.2	12.8	16.3	24.4
1365	2.3	12.1	15.3	11.5	12.2	15.6	11.9	16	22.5
1440	2.3	12.1	15.3	11.5	12.2	15.6	11.9	16	22.5
1440	2.3	14.3	32	14	15.5	33	15	12	35.2
1455	2.3	26	32	29	26.1	31.9	31.6	12	35.2
1470	2.3	29	34.2	32.2	28.3	34.6	34	12.1	34.8
1485	2.3	29.9	34.2	32.2	29	34	34	12.1	34.5
1500	2.3	29.9	34.2	33.5	29.7	34.4	33.9	12.1	34.5
1515	2.3	30.3	34.2	33.5	30	34.4	33.8	12.1	34.5
1530	2.3	30.3	34.2	33.5	30.3	34.4	33.8	12.1	34.5
1545	2.4	30.3	34.2	33.6	30.6	34.3	33.7	12.2	34.5
1560	2.4	30.3	34.2	33.6	30.8	34.4	33.7	12.2	35.5
1560	2.4	31.5	41.5	38	30.5	41.2	36.7	0.9	42
1575	2.4	32	41.5	42	30.6	41.5	40.9	0.9	42
1590	2.4	32.2	41.5	42	34.4	41.6	41	0.9	42
1605	2.4	32.6	41.5	42	36.3	41.6	41	0.9	42
1620	2.4	36.6	41.5	42.2	36.5	41.7	41	0.9	42
1635	2.4	36.6	41.5	42.2	36.2	41.6	41	0.9	42
1665	2.4	36.6	41.5	42.2	34.9	41.7	41	0.9	42
1680	2.4	36.6	41.5	42.2	34.5	41.6	41	0.9	42
1695	2.6	36.6	41.7	42.2	34.5	41.6	41	1	42
1710	2.6	36.6	41.7	42.2	34.5	41.6	41	1	41.9
1740	2.6	37	41.7	42.2	34.5	41.6	40.7	1	41.9
1770	2.6	37	41.7	42.2	34.5	41.6	40.7	1	41.9
1800	2.6	37	41.7	42	34.5	41.6	40.7	1	41.9
1830	2.6	37	42.2	42	34.5	41.6	40.7	1	41.9
1860	2.6	37	42.2	42	35.5	41.7	40.7	1	41.9
1890	2.6	37.2	42.2	42	35.5	41.7	40.7	1	41.9
1920	2.6	37.2	42.2	41	36.5	41.7	40.7	1	41.9
1950	2.6	37.2	42.5	41	36.5	41.7	40.7	1	41.9
1980	2.7	37.2	42.5	41	36.5	41.7	40.7	1	41.9
2010	2.7	37.2	42.5	41	36.5	41.7	40.7	1	41.9
2940	2.7	37.2	42.5	41	36.5	41.7	40.2	1	41.9
2960	2.7	37.2	42.5	41	36.5	41.7	40.2	1	41.6
3000	2.7	37.2	42.5	41	36.5	41.7	40.2	1	41.6
3000	2.7	40	65	50.2	38	64	46	3	65.7

3010	3	42	65	64.1	46.3	65.1	63.2	3.1	65.7
3015	3.1	47.7	65.3	64.6	49	65.5	64.1	3.1	65.7
3020	3.3	48.3	65.3	65.2	52.2	65.2	65	3.1	65.7
3025	3.5	51.1	65.3	65.2	54	65.2	65	3.2	65.7
3035	3.9	53.6	65.3	65.2	55.6	65.3	65	3.2	65.7
3045	4.3	54	65.3	65.6	58	65.3	65	3.2	65.7
3055	4.7	56.2	65.3	65.6	59	65.3	65	3.3	65.7
3060	4.9	58.8	65.5	65.6	59.4	65.3	65	3.3	65.6
3070	5.3	59.3	65.5	65.6	60	65.7	65	3.3	65.6
3085	6	59.6	65.5	65.6	60.8	65.2	65	3.4	65.6
3100	6.7	60	65.5	65.6	61.3	65.2	65	3.5	65.6
3120	7.5	60.9	65.5	65.6	62	65.2	65	3.7	65.6
3120	7.5	61.3	77	66	62.3	78	69	3.7	79.1
3125	7.7	63.3	77	73	63.3	78	75	3.7	79
3130	8	64.6	77	73.5	65	79	75	3.8	79
3135	8.4	64.6	77.6	75.2	65	78.8	78.2	3.8	78.9
3140	8.7	65.2	77.6	75.2	66.2	78.8	78.6	4.0	78.9
3145	9	65.2	77.9	77.3	66.2	79	78.8	4.1	78.2
3160	9.9	65.2	77.9	77.3	67.4	79	78.1	4.2	79.1
3175	10.7	65.2	77.9	77.3	67.4	79	78.6	4.3	79.1
3190	11.7	65.6	78.1	77.3	68.2	79	78.6	4.5	79
3205	12.5	65.7	78.1	77.3	68.3	79	78.6	4.6	79
3220	13.3	68.3	78.1	77.3	70.1	79	78.6	4.7	78.8
3235	14.3	68.8	78.1	77.3	70.4	79	78.6	5.0	79
3345	14.3	69.2	78.1	77.3	71.3	79	78.6	5.1	79
3360	14.3	69.6	78.1	77.6	71.6	79	78.6	5.1	79
3390	14.7	72.2	78.1	77.6	72.3	79	78.6	5.2	79
3405	14.7	72.2	78.6	77.6	73	79	78.6	5.2	79
3420	14.7	72.2	78.6	77.6	73	79	78.6	5.2	78.8
3435	15.1	73.1	78.6	78.2	73.5	79	78.4	5.3	78.8
3465	15.2	73.3	78.6	78.2	73.5	79	78.4	5.3	78.8
3495	15.2	73.5	78.6	78.2	74	79	78.4	5.5	78.6
3525	15.2	73.5	78.6	78.2	74	79	78.4	5.5	78.6
3555	15.2	73.5	78.6	78.2	74	79	78.4	5.5	78
4500	16.1	75.1	75	75.2	72	75.5	75.3	6.0	75.5
4560	16.1	75.1	75	75.2	72	75.5	75.3	6.0	75.5
7440	16.7	75.1	75	75.2	72	75.5	75.3	6.0	75.5

- **Experiment T3:** 2 Layer of TS40 geotextile and Kayseri clay with the density of 1.57 g/cm³

Table A.3 Test data of the experiment T3

Time (min)	Mass of outflow container (g)	H1	H2	H3	H4	H5	H6	H7	H8
0	0	14.4	21.2	14.8	14	21.6	14.5	16	25
15	0	14.4	21.2	14.8	14	21.6	14.5	16	25
30	0	14.4	21.2	14.8	14	18.3	14.5	16.3	24.7
45	0	14.4	21.1	14.8	14	19.7	14.4	16.3	24.7
60	0	14.4	21.1	14.8	14	20.1	14.8	16.3	24.7
75	0	14.4	21.1	14.8	13.9	20.1	14.8	16.3	24.7
90	1	14.3	21.1	14.6	13.9	23.6	15.6	16.4	24.7
105	1	14.3	21.1	16.5	13.7	21.2	14.7	16.4	24.7
120	1.1	14.3	21.1	14.5	13.6	21.3	14.7	16.4	24.3
135	1.1	14.3	24.3	14.4	13.6	21.3	14.7	16.4	24.5
150	1.2	14.3	24.3	12.7	16	26.7	13	16.4	24.5
165	1.2	14.3	24.3	12.7	16	26.7	13	16.4	24.5
180	1.2	14.3	24.3	12.7	16	26.7	13	16.4	24.5
195	1.2	14.3	24.3	12.7	16	26.7	13	16.4	24.5
210	1.2	14.3	24.3	12.7	16	26.7	13	16.4	24.5
225	1.2	14.3	24.3	12.7	16	26.7	13	16.4	24.5
240	1.3	14.3	24.3	12.7	16	26.7	13	16.4	24.5
255	1.3	14.3	24.3	12.7	16	26.5	13	16.4	24.5
270	1.3	14.3	24.3	12.7	16	26.5	13	16.4	24.5
285	1.3	14.3	24.1	12.7	15.8	26.5	13	16.4	24.5
300	1.3	14.3	24.1	12.5	15.8	26.5	12.8	16.4	24.5
315	1.4	14.3	24.1	12.5	15.8	26.4	12.8	16.3	24.5
330	1.4	14.2	24.1	12.5	15.8	26.4	12.8	16.3	24.5
345	1.4	14.2	24.1	12.5	15.8	26.4	12.8	16.3	24.5
360	1.4	14.2	24.1	12.5	15.7	26.4	12.8	16.3	24.4
375	1.4	14.2	24.1	12.5	15.7	26.2	12.8	16.3	24.4
390	1.4	14.2	24.1	12.5	15.7	26.2	12.8	16.3	24.4
405	1.5	14.2	24.1	12.4	15.7	26.2	12.8	16.3	24.4
420	1.5	14.2	24.1	12.4	15.5	26.2	12.8	16.3	24.4
435	1.6	14.2	24	12.4	15.5	26.2	12.8	16.3	24.4
450	1.6	14.2	24	12.4	15.5	26.2	12.8	16.3	24.4
465	1.6	14.2	24	12.4	15.5	26.2	12.8	16.3	24.4
1365	2.3	12.1	15.3	11.5	12.2	15.6	11.6	16	22.5
1440	2.3	12.1	15.3	11.5	12.2	15.6	11.6	16	22.5
1440	2.3	14.3	32	14	15.5	33	14	12	35.2
1455	2.3	26	32	29	26.1	31.9	31.6	12	35.2
1470	2.3	29	34.2	32.2	28.3	34.6	34	12.1	34.8
1485	2.3	29.9	34.2	32.2	29	34	34	12.1	34.5
1500	2.3	29.9	34.2	33.5	29.7	34.4	33.9	12.1	34.5

1515	2.3	30.3	34.2	33.5	30	34.4	33.8	12.1	34.5
1530	2.3	30.3	34.2	33.5	30.3	34.4	33.8	12.1	34.5
1545	2.3	30.3	34.2	33.6	30.6	34.3	33.7	12.2	34.5
1560	2.4	30.3	34.2	33.6	30.8	34.4	33.7	12.2	35.5
1560	2.4	31.5	41.5	38	30.5	41.2	36.7	0.9	42
1575	2.4	32	41.5	42	30.6	41.5	40.9	0.9	42
1590	2.4	32.2	41.5	42	34.4	41.6	41	0.9	42
1605	2.4	32.6	41.5	42	36.3	41.6	41	0.9	42
1620	2.4	36.6	41.5	42.2	36.5	41.7	41	0.9	42
1635	2.4	36.6	41.5	42.2	36.2	41.6	41	0.9	42
1665	2.4	36.6	41.5	42.2	34.9	41.7	41	0.9	42
1680	2.4	36.6	41.5	42.2	34.5	41.6	41	0.9	42
1695	2.4	36.6	41.7	42.2	34.5	41.6	41	1	42
1710	2.4	36.6	41.7	42.2	34.5	41.6	41	1	41.9
1740	2.4	37	41.7	42.2	34.5	41.6	40.7	1	41.9
1770	2.4	37	41.7	42.2	34.5	41.6	40.7	1	41.9
1800	2.6	37	41.7	42	34.5	41.6	40.7	1	41.9
1830	2.6	37	42.2	42	34.5	41.6	40.7	1	41.9
1860	2.6	37	42.2	42	35.5	41.7	40.7	1	41.9
1890	2.6	37.2	42.2	42	35.5	41.7	40.7	1	41.9
1920	2.6	37.2	42.2	41	36.5	41.7	40.7	1	41.9
1950	2.6	37.2	42.5	41	36.5	41.7	40.7	1	41.9
1980	2.6	37.2	42.5	41	36.5	41.7	40.7	1	41.9
2010	2.6	37.2	42.5	41	36.5	41.7	40.7	1	41.9
2940	2.7	37.2	42.5	41	36.5	41.7	40.2	1	41.9
2960	2.7	37.2	42.5	41	36.5	41.7	40.2	1	41.6
3000	2.7	37.2	42.5	41	36.5	41.7	40.2	1	41.6
3000	2.7	40	65	50.2	38	64	46	3	65.7
3010	2.7	42	65	64.1	46.3	65.1	63.2	3.1	65.7
3015	2.9	47.7	65.3	64.6	49	65.5	64.1	3.1	65.7
3020	2.9	48.3	65.3	65.2	52.2	65.2	65	3.1	65.7
3025	3	51.1	65.3	65.2	54	65.2	65	3.2	65.7
3035	3.2	53.6	65.3	65.2	55.6	65.3	65	3.2	65.7
3045	3.2	54	65.3	65.6	58	65.3	65	3.2	65.7
3055	3.3	56.2	65.3	65.6	59	65.3	65	3.3	65.7
3060	3.4	58.8	65.5	65.6	59.4	65.3	65	3.3	65.6
3070	3.6	59.3	65.5	65.6	60	65.7	65	3.3	65.6
3085	3.8	59.6	65.5	65.6	60.8	65.2	65	3.4	65.6
3100	4	60	65.5	65.6	61.3	65.2	65	3.5	65.6
3120	4.1	60.9	65.5	65.6	62	65.2	65	3.7	65.6
3120	4.1	61.3	77	66	62.3	78	69	3.7	79.1
3125	4.3	63.3	77	73	63.3	78	75	3.7	79
3130	4.6	64.6	77	73.5	65	79	75	3.8	79
3135	5	64.6	77.6	75.2	65	78.8	78.2	3.8	78.9
3140	5.3	65.2	77.6	75.2	66.2	78.8	78.6	4.0	78.9

3145	5.6	65.2	77.9	77.3	66.2	79	78.8	4.1	78.2
3160	6.5	65.2	77.9	77.3	67.4	79	78.1	4.2	79.1
3175	7.3	65.2	77.9	77.3	67.4	79	78.6	4.3	79.1
3190	8.3	65.6	78.1	77.3	68.2	79	78.6	4.5	79
3205	9.1	65.7	78.1	77.3	68.3	79	78.6	4.6	79
3220	9.9	68.3	78.1	77.3	70.1	79	78.6	4.7	78.8
3235	10.9	68.8	78.1	77.3	70.4	79	78.6	5.0	79
3345	10.9	69.2	78.1	77.3	71.3	79	78.6	5.1	79
3360	10.9	69.6	78.1	77.6	71.6	79	78.6	5.1	79
3390	11.3	72.2	78.1	77.6	72.3	79	78.6	5.2	79
3405	11.3	72.2	78.6	77.6	73	79	78.6	5.2	79
3420	11.3	72.2	78.6	77.6	73	79	78.6	5.2	78.8
3435	11.7	73.1	78.6	78.2	73.5	79	78.4	5.3	78.8
3465	11.8	73.3	78.6	78.2	73.5	79	78.4	5.3	78.8
3495	11.8	73.5	78.6	78.2	74	79	78.4	5.5	78.6
3525	11.8	73.5	78.6	78.2	74	79	78.4	5.5	78.6
3555	11.8	73.5	78.6	78.2	74	79	78.4	5.5	78
4500	12.7	75.1	75	75.2	74	75.5	75.3	6.0	75.5
4560	12.7	75.1	75	75.2	74	75.5	75.3	6.0	75.5
7440	13.3	75.1	75	75.2	74	75.5	75.3	6.0	75.5

- **Experiment T4:** 1 Layer of PP3000 geotextile and Kayseri clay with the density of 1.58 g/cm³

Table A.4 Test data of the experiment T4

Time (min)	Mass of outflow container (g)	H1	H2	H3	H4	H5	H6	H7	H8
0	0	20.4	21.2	20.2	36	19	26	19.2	31
15	0.4	20.4	21.2	20.2	36	19	21.4	19.2	27.4
30	0.4	20.4	21.2	20.2	30	19	19.9	19.2	26.9
45	0.4	20.4	21.1	20.2	30	19	19.6	19.2	26.8
60	0.4	20.4	21.1	20.2	28	19.6	19.5	19.3	26.8
75	0.4	20.4	21.1	19.9	24.9	19.5	19.5	19.3	26.8
90	0.4	20.3	21.1	19.9	24.9	19.5	18.8	19.3	26.8
105	0.4	20.3	21.1	19.9	24.7	19.5	18.8	19.3	26.8
120	0.4	20.3	21.1	19.9	24.6	19.5	18.6	19.3	26.6
195	0.4	20.3	24.3	19.9	24.6	19.8	18.5	19.3	26.6
250	0.4	20.3	24.3	19.7	26.8	19.8	18.3	19.3	26.6
275	0.4	20.3	24.3	19.7	26.8	19.8	18.3	19.3	26.6
285	0.4	20.3	24.3	19.7	26.8	19.8	18.3	19.3	26.5

300	0.4	20.3	24.3	19.7	26.8	19.8	18.3	19.3	26.5
345	0.4	20.3	24.3	19.7	26.8	19.8	18.4	19.3	26.5
360	0.4	20.3	24.3	19.7	26.8	19.9	18.4	19.3	26.5
375	0.4	20.3	24.3	19.7	26.8	19.9	18.4	19.3	26.5
390	0.4	20.2	24.3	19.7	26.8	20.3	18.5	19.3	26.5
405	0.5	20.1	24.3	19.7	26.8	20.3	18.5	19.3	26.5
420	0.5	20.1	24.1	19.7	26.8	20.3	18.5	19.3	26.5
450	0.5	20.1	24.1	19.5	26.8	20.3	18.5	19.3	26.5
1400	0.5	20.1	24.1	19.5	26.6	15.8	19	19.3	26.5
1440	0.5	20.1	24.1	19.5	26.6	15.8	19	19.3	26.5
1680	0.5	20.1	24.1	19.5	26.6	15.8	19	19.3	26.5
1685	0.5	20.1	24.1	19.5	26.6	15.8	19	19.3	26.5
1685	0.5	17	32	14	18.1	33	15	11	35.2
1700	0.5	29	32	26.7	33.1	31.9	31.6	11	35.2
1715	0.5	29	34.2	27.3	33.1	31.9	31.6	11	34.8
1730	0.5	32	34.2	30	33.4	34	31.6	11	34.5
1745	0.6	32	34.2	30.2	33.7	34.4	32.1	11	34.5
1760	0.6	32.3	34.2	30.2	34	34.4	32.1	11.2	34.5
1775	0.6	32.3	34.2	30.2	34.3	34.4	32.1	11.2	34.5
1790	0.6	32.3	34.2	30.2	34.8	34.3	32.3	11.2	34.5
1805	0.6	32.3	34.2	30.2	34.8	34.4	32.3	11.2	35.5
1805	0.6	31.5	41.5	30.5	36.4	15	34.5	1.1	51
1815	0.6	32	41.5	30.6	38.6	15.8	38.3	1.1	51
1830	0.6	32.2	41.5	30.4	38.6	15.8	38.3	1.1	51
1845	0.6	32.6	41.5	30.4	38.9	15.8	38.3	1.1	51
1860	0.6	36.6	41.5	32.2	38.9	15.8	38.3	1.1	51
1875	0.6	36.6	41.5	32.2	39.3	15.8	38.3	1.1	51
1890	0.6	36.6	41.5	34.9	40.9	15.5	38.3	1.1	51
1925	0.6	36.6	41.5	34.5	40.5	15.5	38.3	1.1	51
1955	0.6	36.6	41.7	34.5	40.5	15.5	38.2	1.1	51
1985	0.6	37	41.7	34.5	40.5	15.5	38.2	1.1	51
2015	0.6	37	41.7	34.5	40.5	15.5	38.2	1.1	51
2045	0.6	37	41.7	34.5	40.5	15.3	38.2	1.1	51
2075	0.6	37	42.2	34.5	40.5	15.3	38.2	1.1	51
2105	0.6	37	42.2	35.5	40.5	15.3	38.2	1.1	51
2135	0.6	37.2	42.2	35.5	40.5	15.3	38.3	1.1	51
2165	0.6	37.2	42.2	36.5	40.5	15.3	38.3	1.2	50.6
2195	0.7	37.2	42.5	36.5	40.5	14.9	38.3	1.2	50.6
2225	0.7	37.2	42.5	36.5	40.5	14.9	38.3	1.2	50.6
2255	0.7	37.2	42.5	36.5	40.5	14.9	38.3	1.2	50.6
3205	0.7	37.2	42.5	36.5	40.5	13.2	38.3	1.2	50.6
3245	0.7	37.2	42.5	36.5	40.5	13.2	38.3	1.2	50.6
3245	0.7	40	65	50.2	38	64	63	3	75.7
3255	0.7	42	65	64.1	46.3	65.1	63.2	3.1	75.7
3260	0.7	47.7	65.3	64.6	49	65.5	64.1	3.1	75.7

3265	0.7	48.3	65.3	65.2	52.2	65.2	65	3.1	75.7
3270	0.9	51.1	65.3	65.2	54	65.2	65	3.2	75.7
3280	0.9	53.6	65.3	65.2	55.6	65.3	65	3.2	75.5
3290	0.9	54	65.3	65.6	58	65.3	65	3.2	75.5
3300	1	56.2	65.3	65.6	59	65.3	65	3.3	75.5
3305	1.1	58.8	65.5	65.6	59.4	65.3	65	3.3	75.5
3315	1.1	59.3	65.5	65.6	60	65.7	65	3.3	75.4
3330	1.1	59.6	65.5	65.6	60.8	65.2	65	3.4	75.4
3345	1.1	60	65.5	65.6	61.3	65.2	65	3.5	75.4
3365	1.1	60.9	65.5	65.6	62	65.2	65	3.7	75.4
3365	1.1	36.3	67	66	30	43	65	2.6	93.5
3375	1.1	35.8	67	73	32.2	45.2	66.4	2.6	93.5
3385	1.1	35.8	67	73	32.2	45.2	66.5	2.6	93.5
3400	1.1	35.8	67.6	73	32.2	45.2	66.3	2.6	93.5
3415	1.1	35.8	67.6	73	32.3	45.2	66.3	2.6	93.5
3430	1.1	35.8	67.9	73	32.3	45.2	66.3	2.6	93.5
3445	1.1	35.8	67.9	73	32.3	45.2	66.3	2.6	93.5
3465	1.1	35.8	67.9	73	32.3	45.2	66.3	2.6	93.5
3480	1.1	36.6	68.1	73	33.6	46.6	66.8	2.6	93.5
3590	1.1	36.6	68.1	73.3	33.6	46.6	66.8	2.6	93.5
3605	1.1	36.6	68.1	73.3	33.6	48.8	66.8	2.6	93.5
3635	1.1	36.6	68.1	73.4	33.6	51.3	66.8	2.6	93.5
3650	1.2	36.6	68.1	73.4	35.2	51.3	66.8	2.6	93.3
3665	1.2	36.6	68.1	73.3	35.2	51.3	66.8	2.6	93.3
3680	1.2	36.9	68.1	73.3	35.2	52.6	66.8	2.7	93.3
3710	1.2	36.9	68.6	73.3	35.2	52.6	67.2	2.7	93.3
3740	1.2	36.9	68.6	73.1	35.6	52.6	67.2	2.7	93.3
3770	1.2	36.9	68.6	73.1	35.6	52.6	67.2	2.7	93.3
3800	1.2	36.9	68.6	73.1	35.7	52.6	67.2	2.7	93.3
4745	1.2	49.9	54.3	66.6	51	66.8	67.5	2.7	93.3
4805	1.2	49.9	54.3	66.6	51	66.8	67.4	2.7	93.3
6245	1.2	49.9	54.3	66.6	51	66.8	67.4	2.7	93.3
7685	1.2	49.9	54.3	66.6	51	66.8	67.4	2.7	93.3
9125	1.2	49.9	54.3	66.6	51	66.8	67.4	2.7	93.3

- **Experiment T5:** 2 Layer of TS40 geotextile and Kayseri clay with the density of 1.60 g/cm³

Table A.5 Test data of the experiment T5

Time (min)	Mass of outflow container (g)	H1	H2	H3	H4	H5	H6	H7	H8
0	0	20.4	21.2	20.2	35	19	24.2	19.2	31
15	0.4	20.4	21.2	20.2	35	19	21.4	19.2	27.4
30	0.4	20.4	21.2	20.2	30	19	20.1	19.2	26.9
45	0.4	20.4	21.1	20.2	26	19	19.3	19.2	26.8
60	0.4	20.4	21.1	20.2	25	19.6	19.4	19.3	26.8
75	0.4	20.4	21.1	19.9	24.9	19.5	19.4	19.3	26.8
90	0.4	20.3	21.1	19.9	24.9	19.5	18.8	19.3	26.8
105	0.4	20.3	21.1	19.9	24.7	19.5	18.8	19.3	26.8
120	0.4	20.3	21.1	19.9	24.6	19.5	18.6	19.3	26.6
195	0.4	20.3	24.3	19.9	24.6	19.8	18.5	19.3	26.6
250	0.4	20.3	24.3	19.7	26.8	19.8	18.3	19.3	26.6
275	0.4	20.3	24.3	19.7	26.8	19.8	18.3	19.3	26.6
285	0.4	20.3	24.3	19.7	26.8	19.8	18.3	19.3	26.5
300	0.4	20.3	24.3	19.7	26.8	19.8	18.3	19.3	26.5
345	0.4	20.3	24.3	19.7	26.8	19.8	18.4	19.3	26.5
360	0.4	20.3	24.3	19.7	26.8	19.9	18.4	19.3	26.5
375	0.4	20.3	24.3	19.7	26.8	19.9	18.4	19.3	26.5
390	0.4	20.2	24.3	19.7	26.8	20.3	18.5	19.3	26.5
405	0.5	20.1	24.3	19.7	26.8	20.3	18.5	19.3	26.5
420	0.5	20.1	24.1	19.7	26.8	20.3	18.5	19.3	26.5
450	0.5	20.1	24.1	19.5	26.9	20.3	18.5	19.3	26.5
1400	0.5	20.1	24.1	19.5	26.7	15.8	19	19.3	26.5
1440	0.5	20.1	24.1	19.5	26.7	15.8	19	19.3	26.5
1680	0.5	20.1	24.1	19.5	26.7	15.8	19	19.3	26.5
1685	0.5	20.1	24.1	19.5	26.7	15.8	19	19.3	26.5
1685	0.5	17	32	14	18.1	33	15	11	35.2
1700	0.5	29	32	26.7	33.1	31.9	31.6	11	35.2
1715	0.5	29	34.2	27.3	33.1	31.9	31.6	11	34.8
1730	0.5	32	34.2	30	33.4	34	31.6	11	34.5
1745	0.5	32	34.2	30.2	33.7	34.4	32.1	11	34.5
1760	0.5	32.3	34.2	30.2	34	34.4	32.1	11.2	34.5
1775	0.6	32.3	34.2	30.2	34.3	34.4	32.1	11.2	34.5
1790	0.6	32.3	34.2	30.2	34.3	34.3	32.2	11.2	34.5
1805	0.6	32.3	34.2	30.2	34.5	34.4	32.2	11.2	35.5
1805	0.6	31.5	41.5	30.5	35	15	34.5	1.1	51
1815	0.6	32	41.5	30.6	35	15.8	38.3	1.1	51
1830	0.6	32.2	41.5	30.4	39	15.8	38.3	1.1	51
1845	0.6	32.6	41.5	30.4	38.9	15.8	38.3	1.1	51
1860	0.6	36.6	41.5	32.2	38.9	15.8	38.3	1.1	51
1875	0.6	36.6	41.5	32.2	39.3	15.8	38.3	1.1	51
1890	0.6	36.6	41.5	34.9	40.9	15.5	38.3	1.1	51

1925	0.6	36.6	41.5	34.5	40.5	15.5	38.3	1.1	51
1955	0.6	36.6	41.7	34.5	40.5	15.5	38.2	1.1	51
1985	0.6	37	41.7	34.5	40.5	15.5	38.2	1.1	51
2015	0.6	37	41.7	34.5	40.5	15.5	38.2	1.1	51
2045	0.6	37	41.7	34.5	40.5	15.3	38.2	1.1	51
2075	0.6	37	42.2	34.5	40.5	15.3	38.2	1.1	51
2105	0.6	37	42.2	35.5	40.5	15.3	38.2	1.1	51
2135	0.7	37.2	42.2	35.5	40.5	15.3	38.3	1.1	51
2165	0.7	37.2	42.2	36.5	40.5	15.3	38.3	1.2	50.6
2195	0.7	37.2	42.5	36.5	40.5	14.9	38.3	1.2	50.6
2225	0.7	37.2	42.5	36.5	40.5	14.9	38.3	1.2	50.6
2255	0.7	37.2	42.5	36.5	40.5	14.9	38.3	1.2	50.6
3205	0.7	37.2	42.5	36.5	40.5	13.2	38.3	1.2	50.6
3245	0.7	37.2	42.5	36.5	40.5	13.2	38.3	1.2	50.6
3245	0.7	40	65	50.2	38	64	46	3	75.7
3255	0.7	42	65	64.1	46.3	65.1	63.2	3.1	75.7
3260	0.7	47.7	65.3	64.6	49	65.5	64.1	3.1	75.7
3265	0.7	48.3	65.3	65.2	52.2	65.2	65	3.1	75.7
3270	0.7	51.1	65.3	65.2	54	65.2	65	3.2	75.7
3280	0.7	53.6	65.3	65.2	55.6	65.3	65	3.2	75.5
3290	0.8	54	65.3	65.6	58	65.3	65	3.2	75.5
3300	1	56.2	65.3	65.6	59	65.3	65	3.3	75.5
3305	1	58.8	65.5	65.6	59.4	65.3	65	3.3	75.5
3315	1	59.3	65.5	65.6	60	65.7	65	3.3	75.4
3330	1	59.6	65.5	65.6	60.8	65.2	65	3.4	75.4
3345	1	60	65.5	65.6	61.3	65.2	65	3.5	75.4
3365	1	60.9	65.5	65.6	62	65.2	65	3.7	75.4
3365	1	36.3	67	66	30	43	65	2.6	93.5
3375	1	35.8	67	73	32.2	45.2	66.4	2.6	93.5
3385	1	35.8	67	73	32.2	45.2	66.5	2.6	93.5
3400	1	35.8	67.6	73	32.2	45.2	66.3	2.6	93.5
3415	1	35.8	67.6	73	32.3	45.2	66.3	2.6	93.5
3430	1	35.8	67.9	73	32.3	45.2	66.3	2.6	93.5
3445	1	35.8	67.9	73	32.3	45.2	66.3	2.6	93.5
3465	1	35.8	67.9	73	32.3	45.2	66.3	2.6	93.5
3480	1.1	36.6	68.1	73	33.6	46.6	66.8	2.6	93.5
3590	1.1	36.6	68.1	73.3	33.6	46.6	66.8	2.6	93.5
3605	1.1	36.6	68.1	73.3	33.6	48.8	66.8	2.6	93.5
3635	1.1	36.6	68.1	73.4	33.6	51.3	66.8	2.6	93.5
3650	1.1	36.6	68.1	73.4	35.2	51.3	66.8	2.6	93.3
3665	1.1	36.6	68.1	73.3	35.2	51.3	66.8	2.6	93.3
3680	1.1	36.9	68.1	73.3	35.2	52.6	66.8	2.7	93.3
3710	1.1	36.9	68.6	73.3	35.2	52.6	67.2	2.7	93.3
3740	1.1	36.9	68.6	73.1	35.6	52.6	67.2	2.7	93.3
3770	1.1	36.9	68.6	73.1	35.6	52.6	67.2	2.7	93.3

3800	1.1	36.9	68.6	73.1	35.7	52.6	67.2	2.7	93.3
4745	1.1	49.9	54.3	66.6	51	66.8	67.5	2.7	93.3
4805	1.1	49.9	54.3	66.6	51	66.8	67.4	2.7	93.3
6245	1.1	49.9	54.3	66.6	51	66.8	67.4	2.7	93.3
7685	1.1	49.9	54.3	66.6	51	66.8	67.4	2.7	93.3
9125	1.1	49.9	54.3	66.6	51	66.8	67.4	2.7	93.3

- **Experiment T6:** Garnular filter mixture and Kayseri clay with the density of 1.59 g/cm³

Table A.6 Test data of the experiment T6

Time (min)	Mass of outflow container (g)	Hydraulic Gradient of the System
0	0	0.99
15	0	0.99
30	0	0.93
45	0	0.93
60	0	0.93
75	0	0.93
90	0	0.92
105	0	0.92
120	0	0.88
135	0	0.90
150	0	0.90
165	0	0.90
180	0	0.90
195	0	0.90
210	0	0.90
225	0	0.90
240	0	0.90
255	0	0.90
270	0	0.90
285	0	0.90
300	0	0.90
315	0	0.91
330	0	0.91
345	0	0.91
360	0	0.90
375	0	0.90
390	0	0.90
405	0	0.90
420	0	0.90

435	0	0.90
450	0	0.90
465	0	0.90
1365	0	0.94
1440	0	0.94
1440	0	2.52
1455	0.4	2.52
1470	1.9	2.42
1485	3.1	2.37
1500	4.4	2.37
1515	4.7	2.37
1530	5	2.32
1545	5.2	2.32
1560	5.4	2.32
1560	5.4	5.06
1575	5.4	5.06
1590	5.4	5.06
1605	5.4	5.06
1620	5.4	4.99
1635	5.4	4.99
1665	5.4	4.99
1680	5.4	4.99
1695	5.4	4.99
1710	5.4	4.92
1740	5.4	4.90
1770	5.4	4.90
1800	5.4	4.90
1830	5.4	4.87
1860	5.4	4.87
1890	5.4	4.87
1920	5.5	4.77
1950	5.5	4.77
1980	5.5	4.74
2010	5.5	4.74
2940	5.5	4.74
2960	5.4	4.74
3000	5.4	4.74
3000	5.7	7.45
3010	15.1	7.43
3015	22	7.43
3020	31	7.43
3025	35.5	7.53
3035	41.9	7.53
3045	47.3	7.53
3055	52	7.56

3060	56.4	7.56
3070	61.1	7.58
3085	65.5	7.59
3100	71	7.59
3120	77.3	7.59
3120	77.3	10.07
3125	90.1	10.07
3130	103.3	10.01
3135	123.9	10.01
3140	134.7	9.99
3145	140.7	9.96
3160	145.2	9.95
3175	150.6	9.94
3190	77.3	9.92
3205	77.3	9.91
3220	77.3	9.90
3235	77.3	9.76
3345	77.4	9.75
3360	77.4	9.75
3390	77.4	9.74
3405	77.4	9.74
3420	77.4	9.74
3435	77.4	9.71
3465	77.4	9.71
3495	77.4	9.69
3525	77.4	9.69
3555	77.4	9.62
4500	77.4	9.58
4560	77.4	9.58
7440	77.3	9.58