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ANALYSIS OF DRAINAGE FACILITIES IN EMBANKMENT DAMS

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BY

MUAZZEZ ÖZLEM GÜLSEROĞLU

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Prof. Dr. Mehmet İshak YÜCE

by

Muazzez Özlem GÜLSEROĞLU

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Muazzez Özlem GÜLSEROĞLU

ABSTRACT

ANALYSIS OF DRAINAGE FACILITIES IN EMBANKMENT DAMS

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Embankment dams have long been a popular choice due to their affordability and ease of construction with readily available materials. In fact, they make up the majority of dams worldwide, accounting for around 65% of all dams. However, because of the materials used in their construction, these structures are not impermeable, which leads to seepage, or the movement of water within the dam body. It has been observed that embankment dams that failed between 1900 and 1975 shared common issues such as piping and seepage, overtopping, and foundation problems. To mitigate seepage, protective filters are typically used in dams to prevent the displacement of one material layer with another and facilitate drainage between layers. The primary goal of filters is to reduce the effects of seepage on the dam body. This study investigated the impact of changes in reservoir water head, filter material permeability, and physical properties of filter on seepage and water head in a dam body for 273 dams with three types of filters: blanket, toe, and chimney. The main dam was designed and its stability was analyzed using PLAXIS 2D, while SEEP/W was utilized to determine seepage and water head in the dam body via the finite element method. The results of this study reinforce the critical importance of effective filter design in mitigating the effects of seepage in embankment dams.

Key Words: Embankment Dams, Seepage, Filters, Plaxis 2D, SEEP/W

ÖZET

DOLGU BARAJLARDA DRENAJ SİSTEMLERİNİN ANALİZİ

GÜLSEROĞLU, Muazzez Özlem
Yüksek Lisans Tezi, İnşaat Mühendisliği Bölümü
Danışman: Prof. Dr. Öğr. Üyesi Mehmet İshak YÜCE
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Dolgu barajlar, ekonomik olmaları ve kolaylıkla bulunabilen malzemelerle inşa edilebilmeleri nedeniyle uzun zamandır popüler bir seçim olmuştur. Öyle ki yaklaşık tüm barajların %65'i ile dünya çapındaki barajların çoğunluğunu oluşturmaktadır. Ancak yapımında kullanılan malzemelerden dolayı bu yapılar tümüyle geçirimsiz değildir, bu da sızıntıya veya suyun baraj gövdesi içinde hareket etmesine neden olmaktadır. 1900 ile 1975 yılları arasında yıkılan dolgu barajların borulanma ve sızıntı, baraj gövdesi üzerinden su taşması ve zemin sorunları gibi ortak sorunları paylaştığı görülmüştür. Barajlarda genellikle bir malzeme katmanının diğeriyle yer değiştirmesini önleyerek ve katmanlar arasındaki drenajı kolaylaştırarak sızıntının etkilerini yatıştırmak adına koruyucu filtreler kullanılır. Filtrelerin temel amacı sızıntının baraj gövdesi üzerindeki etkilerini azaltmaktır. Bu çalışmada, üç tip filtreye (yatay dren, topuk dren ve baca dren) sahip 273 baraj için rezervuar su yükü, filtre malzemesi geçirgenliği ve filtrenin fiziksel özelliklerindeki değişikliklerin sızıntı ve su yükü üzerindeki etkisi araştırılmıştır. Ana baraj tasarlanmış ve PLAXIS 2D kullanılarak stabilitesi analiz edilmiş, sonlu elemanlar yöntemi ile baraj gövdesindeki sızıntı ve su yükünü belirlemek için SEEP/W kullanılmıştır. Bu çalışmanın sonuçları, dolgu barajlarda sızıntının etkilerini azaltmada etkili filtre tasarımının kritik önemini güçlendirmektedir.

Anahtar Kelimeler: Dolgu Barajlar, Sızıntı, Drenajlar, Plaxis 2D, SEEP/W

''Dedicated to my family''

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LIST OF SYMBOLS

A	Cross-sectional area normal to the direction of flow
e	Void ratio
GC	Gravel
i	Hydraulic gradient
k	Darcy's coefficient of permeability
Q	Rate of seepage
S	Saturation degree
SC	Clayey Sand
SG	Specific gravity
SW	Sand
E_{ref}	Modulus of Elasticity
V_d	Discharge velocity
WC_{opt}	Optimum water content
WC_{sat}	Saturated water content
c_{ref}	Cohesion
p_d	Dry density
p_{sat}	Saturated density
p_w	Density of water
v_{nu}	Poisson ratio
γ_{sat}	Saturated weight
γ_{unsat}	Unsaturated weight
φ_{ph}	Angle of friction

LIST OFABBREVIATIONS

ANN	Artificial Neural Network
B	Blanket
BEM	Boundary Element Method
BFC	Boundary Fitted Coordination
C	Chimney
FEM	Finite Element Method
FEMA	Federal Emergency Management Agency
H	Horizontal
ICOLD	The International Commission of Large Dams
T	Toe
USACE	USACEs
USBR	U.S. Bureau of Reclamation
V	Vertical

CHAPTER 1
INTRODUCTION

1.1 The History of Dams

Survival has been one of the most fundamental instincts of humanity since the dawn of time. To maintain this, one could claim that water is a necessary substance. Therefore, humanity has been looking for ways to dominate the water. In the beginning, humans dwelt nearby freshwater resources such as rivers, lakes, etc. Their settlement then became a source of water after they discovered how to direct it. Canals built by humans were used to gain control of the water. However, diverting the water was not always sufficient, and it was occasionally required to block or store it. It was this manner that led to the creation of dams. According to Britannica, one of the world's largest encyclopedias, a dam is “a structure built across a stream, a river, or an estuary to retain water.” Dams, as defined, are impermeable or semipermeable structures built for a variety of functions such as water delivery, flood control, sediment management, electricity production, etc. With time, dams have changed in purpose, volume, and the materials used in their construction, reaching the structures that are defined today.

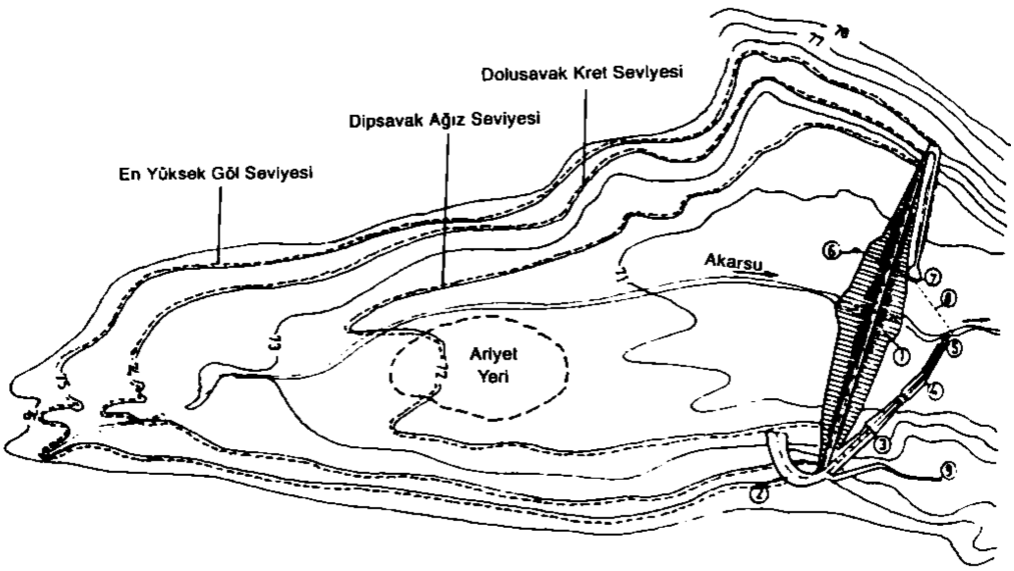


Figure 1.1. A Classical Plan of A Dam (Yanmaz, 2001)

Mesopotamians constructed irrigation channels and dams around 6000 BC, marking the beginning of the history of dams. (Yüce and Yüce, 2016) Then, in the 4th millennium BC, the Jawa Dam was built to increase irrigation production (Brown and Jackson, 2023). The dam was constructed with masonry and earthen materials in the Black Deserts of Jordan. Another known oldest dam is the Sadd el-Kafara Dam in Cario dating from 2950 to 2750 BC. In this instance, the beginning of dam history is derived from the remnants of the structure that have been preserved. With an 11-meter height, 106-meter crest length, and 24 meters upstream and downstream masonry walls, the Sadd el-Kafara Dam had a reservoir capacity of over 5.6 hundred thousand cubic meters. The ancient Egyptians constructed the dam to control floods, but it failed to meet its intended purpose. After a short period of use, overtopping ceased the existence of the dam. In the first millennium B.C., Mesopotamian dams controlled water flow in canals. After that, the Sabeans, an ancient group of South Arabians, showed themselves with the Marib dam which was built to irrigate the surrounding lands. Another ancient Arabian group, the Nabateans, discovered the benefits of silt in agriculture and constructed dams to accumulate silt. Hence, as can be seen in the examples, water storage for use in dry seasons was not one of the primary intentions at the beginning of the dam construction history. Despite these ancient structures being built for different purposes, they were formed from akin materials, wood, masonry, and earth or a combination of these materials. Afterwards, the Romans came to the fore of the stage of history. Their engineering knowledge was based on the Greeks but they took construction techniques a step further using cement made of pozzolana and limestone. As a result of this new material, the Romans changed the way the dam was constructed by designing gravity, arched, and buttressed dams. There was also a rise in earth dams with spillways during their era. Then Muslim engineers began to design dams with mills which is one of the earliest examples of hydro-power systems in dams. They called Pul-i Bulaiti this system and they preferred these structures to provide sufficient water head. Irrigation was the general purpose of these dams. This scheme was altered by Spanish engineers by constructing high dams to store water. This period is well illustrated by the Alicante dam, which was constructed in 1594 and remained the highest in the world for 300 years. There is also the Almendralejo dam which is a noteworthy example as one of the earliest buttress dams and one of the first dams designed hydro-power device in its body (Smith, 1972).

Figure 1.2. The Ruins of Sadd el-Kafara Dam (Smith, 1972)

Dams were preferred because of their water-powering feature because mining engineering operations held a special place in German engineering during the Middle Ages and the Renaissance. The French contributed hydro-power machines, which are similar to water wheels, to dam engineering. Italy was well known for its flood-control dams, one of which, the Ponte Alto dam, is considered one of the earliest arch dams in Europe, except for those built in Spain (Smith, 1972).

Figure 1.3. The Almendralejo Dam (Smith, 1972)

Modern engineering expertise and the Industrial Revolution altered the dams in the 19th century. Recognizing the behavior of cohesive soils through A. W. Skempton's studies enhanced earth dam design. Following that, the utilization of stress analysis methodologies made dam design more exact and trustworthy. Although this evolution began with gravity dams, it was subsequently observed in arch dams. The development of turbines and electric generators gave rise to early hydroelectric dams in Europe, of which Italy was at the forefront due to its significant hydro-power potential. Over the past century, the number of dams doubled, and basic dam design standards have been developed. While the number of dams has increased, it has decreased in diversity (Smith, 1972). During this time, high dams such as the Hoover Dam, Salt Springs Dam, and Roosevelt Dam were constructed. Dam construction records have been broken, and larger, more complicated, and more difficult dams have been created. In the future, there will be many more constructions that will be astonishing.

1.2 Classification of Dams

Dam construction was primarily limited by tinder, masonry, and earth used early in dam engineering history. The capabilities of dams have been constrained by the characteristics of these materials. Thus, in the beginning, dams are classified according to the materials used to construct them. With the invention of cement and mortar, the limits that hampered dam design and construction broadened, and dams altered and diversified. In light of the increasing diversity of dam construction systems, multiple characteristics are being used to classify them. A classification based on the type and materials could be divided into four main types: gravity dams, arch dams, buttress dams, and embankment (earth) dams. Another classification could be done by focusing on the purpose of the construction such as a tailing dam, storage dam, diversion dam, coffer dam, and detention dam. In addition, the size of the dams is generally used to categorize them. The International Commission of Large Dams (ICOLD) defines a dam as a small dam if it is less than 10 meters high. A large dam measures between 10 meters and 50 meters in height and dams higher than 50 meters are entitled as high dams (Yanmaz, 2001) In addition to categorization, ICOLD provides statistical data on dams. For example, based on a study on 58,713 dams, it was discovered that 39,110 dams have specified functions, and some dams serve more than one purpose at the same time. In the classification made among dams serving a single purpose, almost half of them were built for irrigation purposes, followed by dams built for hydroelectric power generation. An illustration of dams and the purpose for their construction is shown in Figure 1.4.

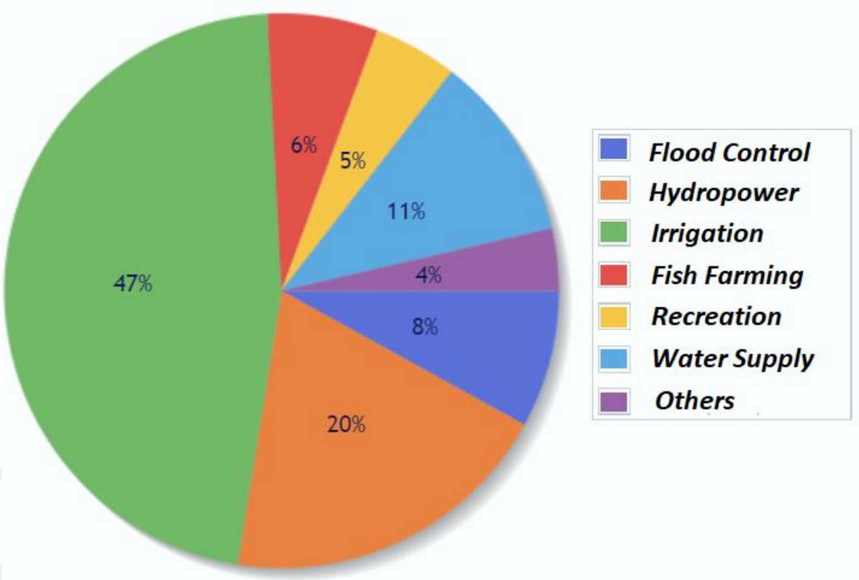


Figure 1.4. The ratio of dams with their purposes (ICOLD, 2023)

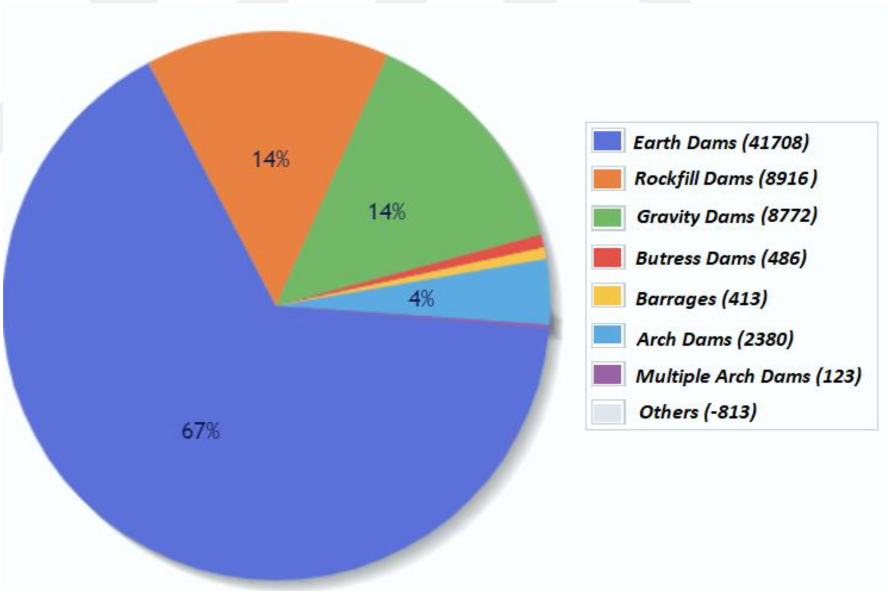


Figure 1.5. Types of the dams with their ratio (ICOLD, 2023)

Along with their purpose in the research that ICOLD did, dams are also classified according to their types in the main classification procedure. The study will focus primarily on the problem of embankment dams, which constitute the dominant majority with 65%. This demonstrates how critical it is to comprehend this dominating type, its working mechanisms, and its flaws. In the next section, embankment dams will be discussed in detail.

1.2.1 Embankment Dams

Embankment dams have been the most frequent form of dam for many years since the materials required for construction could be borrowed from nearby construction areas. Essentially, the material is gathered from the earth's surface and constructed to serve as a barrier against water flow. Among the numerous advantages of embankment dams are the use of local materials, the familiarity with the design procedures, the accessibility of the equipment used, the ability to be built on a variety of foundations, and the reduced risk of settlement when compared to other types of rigid dams. Embankment dams have certain disadvantages in addition to their advantages. Because it has low resistance to flow from the peak, or overtopping, it is necessary to design and construct a structure that is difficult to design and construct, such as a spillway. A full-performance operation cannot be achieved if sufficient compression is not carried out during construction, and regular maintenance is required after completion (Stephens, 2010).

Historically, the first designed dams were homogeneous structures, and they have not survived to the present day in the construction of embankment dams. Because it is well known that these earth constructions have a certain degree of permeability, even if they are designed to block water flow. And their permeability has frequently resulted in the termination of their existence. For this reason, studies have been carried out on the improvement of these structures throughout history they have progressed from homogenous forms to more complicated and layered structures. At present, there are two main categories of embankment dams. They are classified according to their basic material, and further separated into subcategories based on whether they have impermeable layers or the location of these layers:

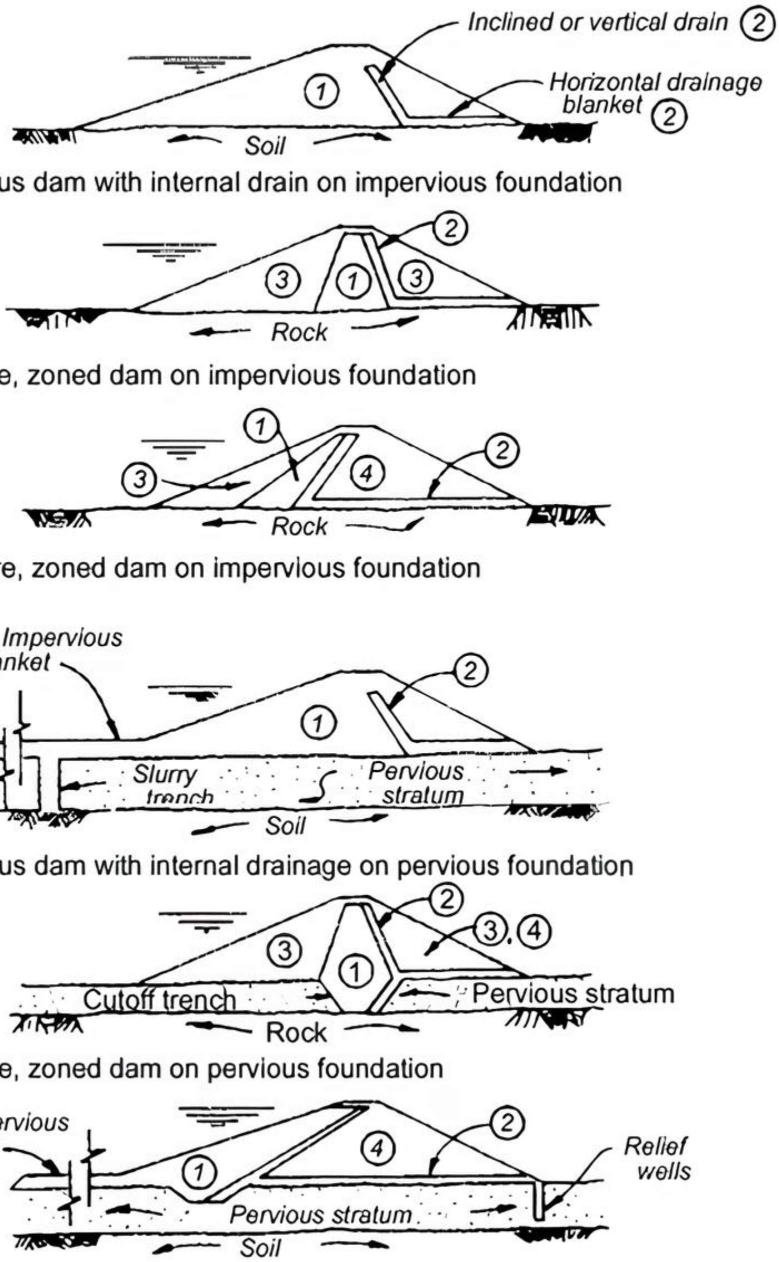
- Earth-fill dams
  - Simple embankment
  - Zoned embankment
  - Diapgragm type embankment
- Rock-fill dams
  - Impermeable-face

- Impermeable-earth core

(Yanmaz, 2001)

Homogeneous embankment dams are constructed from a single material. Except for the filter material, the material used in construction must be impermeable to prevent water flow. However, in the majority of homogenous embankment dam designs, permeable materials are obligated to be used as embankment material. Zoned embankment dams are intended to take advantage of the characteristics of diverse materials. Dams of this type are commonly built in soil-rich areas. Different kinds of materials have different advantages and disadvantages. For example, clay is one of the most common materials that is used in embankment dam construction. But at the same time, clay is fertile material. So, engineers do not prefer to use a huge amount of clay in the body of the dam, and they developed a zoned dam design. Impervious core, downstream filters, drainages, rock fills, and gravel fills are a general part of a zoned earth fill dam. The combination of these parts with the right soil selection enhances safer, more stable, and economical designs.

Material for embankment dam construction is often obtained from the site where the dam will be built or from nearby points. However, because various materials must be utilized for different regions of the dam, the material required may not always be available in the location where the dam will be constructed. Dams can occasionally be constructed using composite structures, meaning that not all of the construction is comprised of earth. In a standard embankment dam, embankments are generally designed with pervious materials such as rock, gravel, and silt. Materials used to create the impermeable layer to prevent permeability could include asphaltic concrete, reinforced concrete, metal, earth fill, and geomembrane. The drain section, which will be discussed in depth later, is made of fine-grained soil particles such as silt. It is important to note that the design of these dams, which include multiple sections and different materials, utilizes the strengths of each material while eliminating the weaknesses of the others.



a. Homogenous dam with internal drain on impervious foundation

b. Central core, zoned dam on impervious foundation

c. Inclined core, zoned dam on impervious foundation

d. Homogenous dam with internal drainage on pervious foundation

e. Central core, zoned dam on pervious foundation

f. Zoned dam with upstream impervious zone on pervious foundation

Note: Sections are modified from those presented in Fig. 1-1, EM 1110-2-2300, Dept. of the Army, Corps of Engineers, May 10, 1982

LEGEND:

① - Zone 1, impervious soil

② - Zone 2, filter drain material (may require a two-stage system - usually processed sands and gravels)

③ - Zone 3, pervious soil (sands and gravels)

④ - Zone 4, random soil (requires adequate engineering properties, but plasticity and gradation are less critical considerations)

Figure 1.6. Earthfill Dam Sections (USBR, 2012)

1.2.1.1 Safety of Embankment Dams

It is known that the Kariba dam, the largest dam in the world, stores 185 billion cubic meters of water. Understanding the potential devastation caused by a rapid flow of such a large quantity of water is sufficient to appreciate the importance of building dams on a reliable basis. It appears that the "flood of Arim", which formed as a result of the collapse of the Marib dam between 570-575 AD and is described in the Qur'an, the holy book of Muslims, provides an excellent illustration of the dangers of dams (Zeidan, 2023). The Puentes Dam, one of the dams whose destruction is documented in history, killed 608 people, destroyed 1800 buildings, and destroyed 40000 trees in 1802 (The Editors of Encyclopaedia Britannica, 2023). On May 31, 1889, another calamity known as the "Johnstown flood" occurred due to overtopping induced by heavy rain in the Southfork dam. There were 2,209 deaths and 17 million dollars in damage. An event that ranked among the top 6 deadliest catastrophes in history occurred in Henan province, China, in 1975, caused by the Banqiao dam failure. Banqiao Dam, which stood 118 meters tall and had a volume of 492 million cubic meters, collapsed during Typhoon Nina, along with 61 other dams. As a result of this destruction, 26,000 people were killed during the flood and 145,000 others died as a result of diseases caused by a lack of access to clean water. It is believed that 220,000 people died in all (The Editors of Encyclopedia Britannica, 2014). The magnitude of the disasters that can be caused by the failure of dams can be explained by the destruction created by these examples.

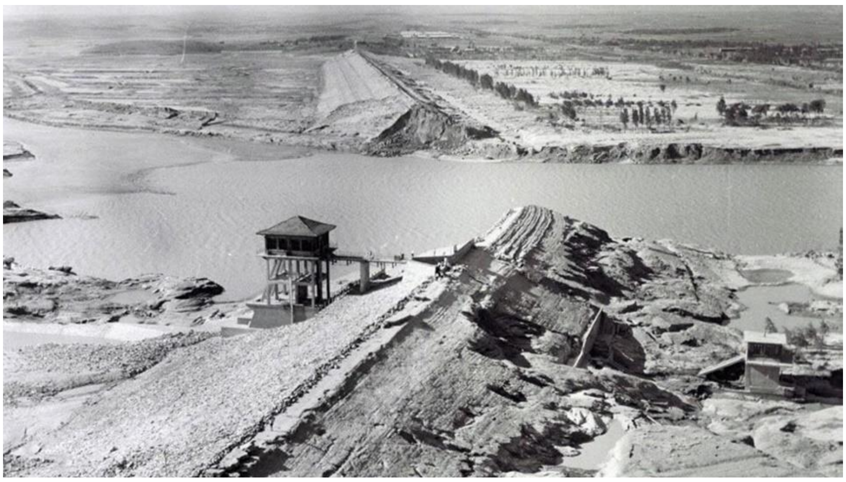
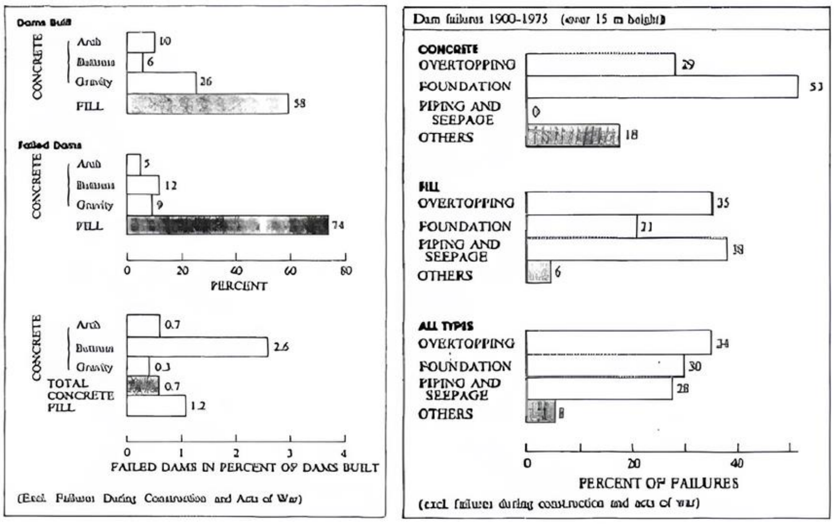


Figure 1.7. Banqiao Dam After Failure (Higginbottom, 2019)

It has been explained before that more than half of the dams in the world are represented by embankment dams. The safety of these structures must be ensured to safeguard human life, to foresee the damage they may cause to the environment, and to protect ourselves from material and moral losses. There are several reasons for dam failure, some of them are primary causes of dam failure, and others are secondary. The knowledge of importance is necessary to take precautions in economic design. The deformation, land subsidence, shear strength, seepage, internal erosion, and piping could be summarized as basis problems. Some problems that occur due to improper embankment materials and construction methods, inadequate compaction, and inaccuracy of the placing of the material are some undesirable conditions in dam construction. Engineers do lots of calculations, and research before and during the dam design. But exceptional and unforeseen actions could arise. Overtopping, earthquakes, rupture of a dam upstream, and construction delays may cause dam failure. The structural behavior of the dam could be inadequate: problems on other watertight systems than the core and transition zone, deficiency in slope protection, inappropriate design in bonding between concrete structures and bordering embankments, etc.



(a) (b)

Figure 1.8. ICOLD Dam Failure Statistics (a) Dam Types in Western Europe and USA in 1900-1960 (b) Dam Failures 1900-1975

According to ICOLD research, 74% of the 58% of embankment dams constructed in the United States and Western Europe between 1900 and 1960 failed during construction or because of war. Data published in another research indicates that earth dams that collapsed worldwide between 1900 and 1975 were due to problems related to piping and seepage, overtopping, and foundation difficulties as could be seen in Figure 1.8.

A study, whose results are presented in Table 1.1, examined 11 192 large fill dams built until 1986 to identify the numerical and proportional equivalents of their failure modes. As a further investigation of this data, it would also be worthwhile to take a look at the failure modes to better understand it. Embankment dam failure could be examined in three categories:

1. Hydraulic Failure
2. Structural Failure
3. Seepage Failure

Hydraulic failures are erosive actions in the embankment of a dam due to uncontrolled water flow. It occurs when the water head rises excessively and starts to overflow from the top of the dam. Wave erosion type of failure induces the decrease in embankment cross section area by the wave actions. The top erosion type of failure is the erosion of the downstream toe of the embankment. This type causes undesirable spillway outlet discharge. The gullying type of failure is the erosion in the embankment slope due to rainfall.

The rupture of the embankment or foundation causes structural failure. Sloughs, bulges, cracks, or other irregularities are some types of structural failure. These types of imperfections are needed to be taken seriously because they are major signs of failure. Large cracks, major settlements, and major slides occur suddenly and villages near the dam can be destroyed and people can lose their lives. Sometimes plants could be a reason for a dam failure. Tree growth on the embankment is induced disintegration of the dam surface. Sometimes, hydraulic failure and seepage failure could occur to the tree growth.

Seepage is one of the major reasons for dam failure directly or implicitly. To understand seepage failure, it is necessary to have detailed information about soil mechanics, the concept of stability, and the definition and causes of internal erosion.

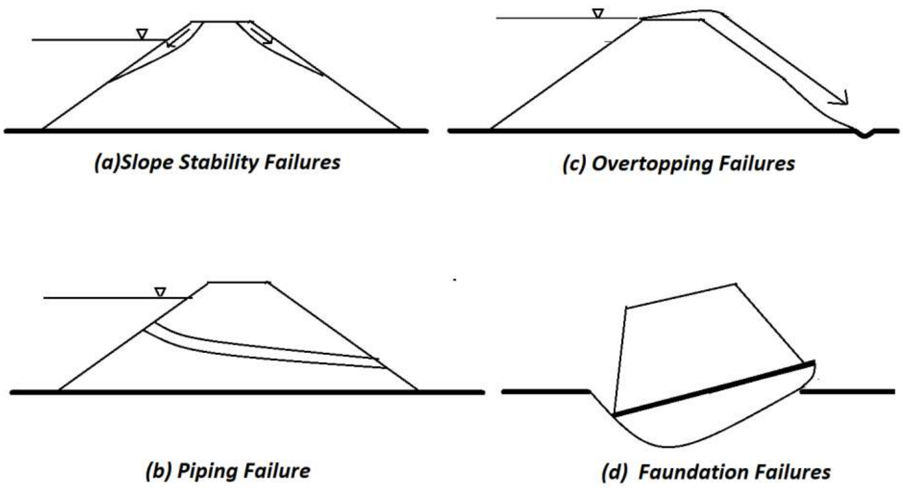


Figure 1.9 Failure Mechanisms of the Embankment Dams

Taking a look at Table 1.1 and examining the statistics, it is apparent that the most common reason for failure is piping, which accounts for 41.6% of the total failure rate. It is followed by overtopping with 35.9%. Next comes the problem of spillways or gates which account for 12.8% of the cases. Slide, earthquake, and liquefaction represent the remaining low rates. It was explained that the major problem, piping, was caused by the displacement of soil particles caused by a long-term leak, as well as the movement of soil particles along a channel through which water flows, and the formation of a ground void. In other words, the seepage, which is the underlying cause of this failure mode and many other dam deformations, should be known in terms of dam safety and precautions should be taken to prevent it from occurring.

Table 1.1. Embankment Dam Failure Statistics (Foster et al., 2000)

			% of failure	
Mode of Failure	**All failures**	**Failure in operation**	**All failures**	**Failure in operation**
Overtopping and appurtenant				
Overtopping	46	40	35,90	34,20
Spillway-gate	16	15	12,50	12,80
Subtotal	62	55	48,40	47,00
Piping				
Through embankment	39	38	30,50	32,50
Through foundation	19	18	14,80	15,40
From embankment into foundation	2	2	1,60	1,70
Subtotal	59	57	46,10	48,70

Slides				
Downstream	6	4	4,70	3,40
Upstream	1	1	0,80	0,90
Subtotal	7	5	5,50	4,30
Earthquake-liquefaction	2	2	1,60	1,70
Unknown mode	8	7		
Total no. of failures	136	124		
Total no. of failures where the mode of failures known	128	117		
No. of embankment dams	11192	11192		

1.3 Seepage

Primary dam designs were not completely impervious by their construction materials and construction area when the first dam designs were researched. In primary dams, a great deal of water flow paths were present in the dam structure. In this manner, water from the upstream shell leaked into the downstream shell of the dam. It is called seepage or seepage. A variety of research has been conducted over the years about the stability and strength of dams, and it has been determined that the decrease in seepage flow in embankment dams has beneficial effects. These are avoidance of corrosion, cracks, slide, settlement, and, increment of water storage yield. Understanding the seepage concept has led to more advanced dam designs. But still, seepage problems could occur in the embankment dam. Understanding the causes and process, monitoring seepage, and taking precautions are important to solve seepage problems and avoid disaster. Seepage occurs in an embankment dam when:

- Insufficient foundation conditions (high permeable foundation or bedrock),
- Lack of recognition of foundation conditions,
- Lack of quality control during the construction.
- The pore pressure of the bottom is higher than the weight of the overlying soil (the overburden pressure),
- Breaches of breaks are caused by uplift force,
- Soil particles move or flow toward cracks or other defects in the soil or bedrock,
- Hydraulic flow erodes the particles,
- Groundwater dissolves soluble bedrock in the foundation,

- Maintenance could not be performed,
- Monitoring systems are inadequate.

The problems caused by the seepage in the dams need to be understood in conjunction with understanding the cause of this seepage in the dams as well as the consequences of this seepage in the dams. Failure modes of dams refer to the permanent effects of seepage. There are four main types of failure modes:

1. Uplift, Heave, or Blowout
2. Piping
3. Internal Erosions
4. Seepage Pressure and Saturation

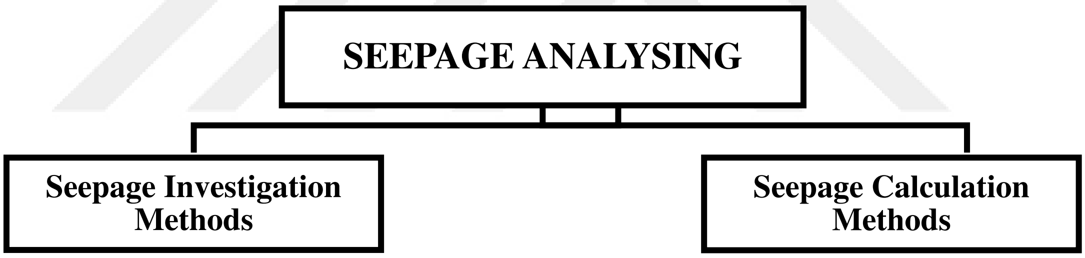
Generally, dam foundations are heterogeneous materials, they consist of various kinds of soils, but one of them is dominant. The heterogeneity of soil could cause different uplift forces between the layers. When the overburden pressure created by the weight of the overlying soils exceeds the pore pressure on the bottom of the confining layer, failure occurs. Commonly occur in sandy soils, hydraulic gradient increase, sand particles that fill gaps between coarser soil particles, is carried through the surface by the water flow. It is called a blowout.

Another failure mode of piping occurs when soil particles move as a pipe through the downstream toe of the dam. Unfiltered dam exit is the major cause of this failure. Cohesionless soil particles begin decomposition by the seepage and separated particles are carried with water as a pipe or tunnel through the exit. This situation causes pore pressure to increase on the foundation of the dam, tunnels or pipes may be expanded and the dam could fail. There are some necessities for piping to occur. There must be a seepage path in the foundation or body of the dam, the hydraulic gradient must be higher than the cohesion force between soil particles, there must be an unfiltered or unprotected exit, and, soils must form as a pipe around the water flow.

Internal erosion processes occur in embankments of a dam, foundation, and contacts between layers of bedrock. Internal erosion is caused by soil particles being removed by slaking, and certain soil particles being eroded by high-velocity water flow. As a result of this process, fractures, and faults develop in the embankment. Another factor is that all dams sink during and after construction. This settlement is not always consistent. When fill material is heterogeneous, soil layers lose consistency during settling and cracks may emerge. Internal erosion might be caused by a variety of materials due to tensile strength variations between earth fill and rock components. These contact sites are vulnerable to hydrostatic pressure, which may result in interior deterioration.

Dam failure may occur as a result of the embankment and abutment sliding, retaining wall failures, canal linings, spillway chutes, and foundation blowout. Sharp slopes can be seen on some embankment dam abutments. When the water head rises upstream of the dam, the embankment under the phreatic surface becomes saturated. It might be the cause of seepage flow downstream of the dam and embankment failure.

Seepage anomalies generally have visual effects such as wet areas, and settlements in the dam body, but sometimes they may occur in a location that can not be observed. For that reason, many kinds of seepage instrumentation and calculation methods have been developed.



Seepage Investigation Methods:

1. Surface Monitoring Systems
2. Dye Tracing
3. Temperature
4. Electrical Resistivity and Self-potential Methods
5. Electromagnetic Profiling
6. Remote Sensing Applications
7. Surface Discharges
8. Surface Deformation
9. Photography, Video Inspections of Conduits and Penetrations
10. Intrusive Methods

Seepage Calculation Methods:

1. Solving Laplace and Darcy Equations
2. Mathematical Solutions
3. Numerical Computer Solutions
4. Graphical Flownet Construction

1.3.1 Seepage Investigation Methods

Seepage can lead to sinkholes, differential settlements, and karstic failures that can be monitored by surface monitoring systems. Deformation of the surface may indicate seepage flows in the earth or the dam's foundation. Surface deformation may result in seepage flowing through the ground or the foundation of the dam. These observable deformations can give us information about seepage. Geotechnical tests could be used in the determination of seepage deformation in an embankment. This method is generally preferred to understand the degree of disintegration of embankment soil. Engineers could also be able to get information on the seepage ratio by analyzing the change in the total head. Dye tracing can be used to determine seepage pathways in embankments, abutments, or foundations; flow velocity could be measured using the dye tracer system.

There is a temperature difference between the water on the riverside and the water inside a dam. The difference in temperature between the water on the riverside and the water inside the dam provides reliable knowledge about seepage. When water flows through the dam, it is temperature changes, discharge location can be determined easily by comparing these values.

An electric potential generated by fluid flow is recorded by a survey line at the surface and can be compared between reservoir levels to determine the direction of seepage flow. Because air-filled features create low conductivities and water or clay-filled features produce high conductivities, seepage routes can be detected by low or high conductivities.

The development of technology has made it possible to monitor seepage areas using smaller video cameras. Such small cameras can be positioned in a manner to provide actual and periodic visual observations. Visual supervision and monitoring of seepage from embankment dams can be accomplished by remote sensing applications, which are extremely rare and beneficial. For the dam site to be monitored during its entire life cycle, advanced-level monitoring systems are necessary. For this purpose, scientists collected data from the site of the dam using infrared, ultraviolet, and other electromagnetic radio frequency spectrums.

1.3.2 Seepage Calculation Methods

Seepage calculation methods are used to evaluate the impact of seepage on a dam, as well as to locate probable seepage pathways. There are several techniques for calculating the seepage problem. The calculation technique that will be used in the analysis must be thorough, logical, and practical. To ensure the correctness of the results, seepage analysis must be performed using several calculating methods.

Darcy's law, developed in 1856, was the basis of the earliest seepage analysis methods. Later, Laplace law was developed based on Darcy's law. Darcy's law does not apply to unsaturated materials or flow through fractures or cracks. The Laplace equation can be applied to porous, fully saturated, and consolidated soils, and it can also be applied to laminar flow. The Laplace equation can be applied to two-dimensional or three-dimensional flow, which makes it possible to give more realistic results. Engineers combined these equations for different conditions calculation.

$$Q = k * i * A \tag{1.1}$$

and

$$V_d = \frac{Q}{A} \tag{1.2}$$

Q = rate of seepage ($cm^3/\ sec$)

V_d= discharge velocity (cm/sec)

k = Darcy's coefficient of permeability (cm/sec)

i = hydraulic gradient

A = cross-sectional area normal to the direction of flow (cm^2)

Formula 1-2 Darcy’s Law

$$\frac{\delta^2 h}{\delta x^2} + \frac{\delta^2 h}{\delta y^2} + \frac{\delta^2 h}{\delta z^2} = 0 \tag{1.3}$$

Formula 3 Laplace Equation

Mathematicians have been interested in the Laplace equation, there are many forms of this equation to solve simple problems. But there every day new methods are developed by mathematicians to solve complicated problems. New approximate methods are generally specialized for unique dam designs.

In this study, the Numerical Computer Solution Method is preferred to analyze the seepage in a dam project. Because using the equation and mathematical solution necessitates making lots of assumptions to simplify operations and results indicate in a limited state. Dam projects are more complex and detailed works. Computer programs could use various algorithms at the same time and they could solve integrated situations. Modelling 2D or 3D plotting gives more realistic and apparent results. MODFLOW, SEEP/W, PLAXIS, ANSYS, PDEase2D, and SVFLUX are some of these programs.

By drawing a flow net, it is possible to estimate the seepage and can even be used to solve the Laplace equation. By using a visual profile, it is possible to investigate the seepage region as well as solve the Laplace equation. Drawing a graphical flow net requires certain information such as the geometry of the area, the boundary conditions at the boundary, the assumptions that need to be made, as well as the anisotropic permeability that must also be accounted for to develop Laplace's equation.

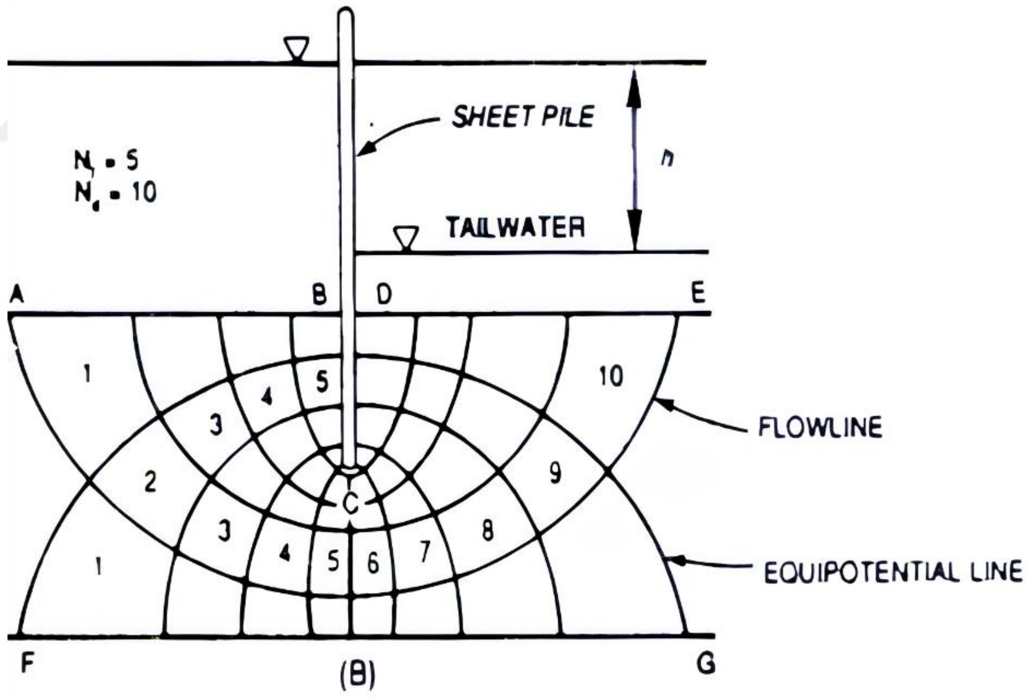


Figure 1.10. An Example of Graphical Flownet Design (Wright, 1990)

1.3.3 Prevention and Control Seepage

It is not possible to prevent seepage in embankment dams without a completely impermeable structural element. However, there are some preventive or control methods. Considering these methods while designing the dam, possible major problems caused by seepage can be avoided. Designing cutoffs, drainage and filter layers, reduction of pressure and piping potential, and using crack stoppers are some of these methods.

Cutoff systems, which are formed by the interlocking of the plates along the edges that allow a continuous wall to be formed, are used to keep the seepage under control by forming an impermeable layer. Ideally, cutoff systems should be located between the reservoir and the center of the dam and should be designed to work with the main material of the dam. A sheet pile made of steel is the most common type in use today. Another cutoff construction style is the secant pile cutoff wall, which consists of a column line filled with concrete and is less common than other forms. Another type of cutoff constructed with the slurry trench method is also preferred because it can be used in existing dams to prevent leaks and improve their condition. In rock structures or foundations, grouting is sometimes applied because it reduces permeability by decreasing the separation distance between the permeable slits. However, if applied incorrectly, grouting can create more problems since it can expand the permeable slits. Geomembranes are another method that could be used to prevent seepage in the body of the dam and they can use in existing dams.

One of the ways to avoid the problems created by seepage is to control the pore pressure it will create. Relief wells and trench drains are two methods used for this purpose. Due to their large area and effectiveness in preventing seepage, trench drains are the first choice. However, they cannot be used at depths with high-pressure conditions. In these conditions, relief wells are used as a pressure control method. An additional method of controlling seepage in dams is to prevent piping, another phenomenon that occurs due to leaks in dams. Reducing the slope of the downstream part of the embankment dam can also extend the path of seepage, thereby controlling it and preventing piping. Furthermore, reducing the seepage in the dam body as well as the possibility of internal erosion could also be achieved by preventing cracks in the dam body. Last but not least, it will examine the drainage and filter elements of dams, which are the primary focus of this study, and which are indispensable components of dams that prevent seepage damages from occurring.

1.3.3.1 Filters and Drains

History has used filter and drain as different words at different times as structures with different functions. However, in addition to working as a filter in the dam, the filter systems utilized today also provide drainage. As a result, the filter is employed to describe a structure that contains the drainage concept. The word filter is used in this text based on this definition. Filters are structural elements used to limit the movement of the soil particles inside the dam, consisting of coarse-grained soil in or adjacent to the dam body, and to provide drainage. During the design of an embankment dam, one of the most important considerations is keeping the pore pressure low due to seepage and preventing soil particles from moving inside the dam. Filter structures designed with this in consideration are one of the most costly materials used in the dam. For this reason, it is desirable to keep the dimensions to a minimum for economical dam design.

There is a need for a filter if there is a risk of differential settlement, a risk of exposure to liquefaction, or if the fill or ground is composed of dispersive clay, the dam core is composed of non-plastic materials, the foundation is constructed of erodible soil, and the dam is constructed upon active faults. Filters come in a variety of types depending on the purpose, characteristics, and material of the dam. Reclamation (2007a) classifies filters as:

1. Drainage Filters (Class I)
2. Protective Filters (Class II)
3. Choke Filters (Class III)
4. Seismic Class Stoppers (Class IV)

Drain filters are filters that are used to slow or stop the flow of water in a dam. Toe drains are one such example. Protective filters are used in dams to prevent the displacement of one material layer with another and to facilitate drainage between the layers. This category includes chimney and blanket filters. Unlike protective filters, choke filters are interlayers that do not need permeability. In other words, it serves only to keep particles from moving between layers. Seismic crack stoppers are filters designed to prevent fractures caused by seismic motions. It is made of coarse-grained soil and is intended to prevent cracks (FEMA, 2011)

In this study, filters were designed for drainage. These were designed as coarse-grained layers in a dam body, that hold soil particles and allow water to flow out. Drainage filters are categorized by their shape and place in the dam body into three chapters as it could be seen in Figure 1.11:

- Toe Drainage
- Blanket Drainage
- Chimney Drainage

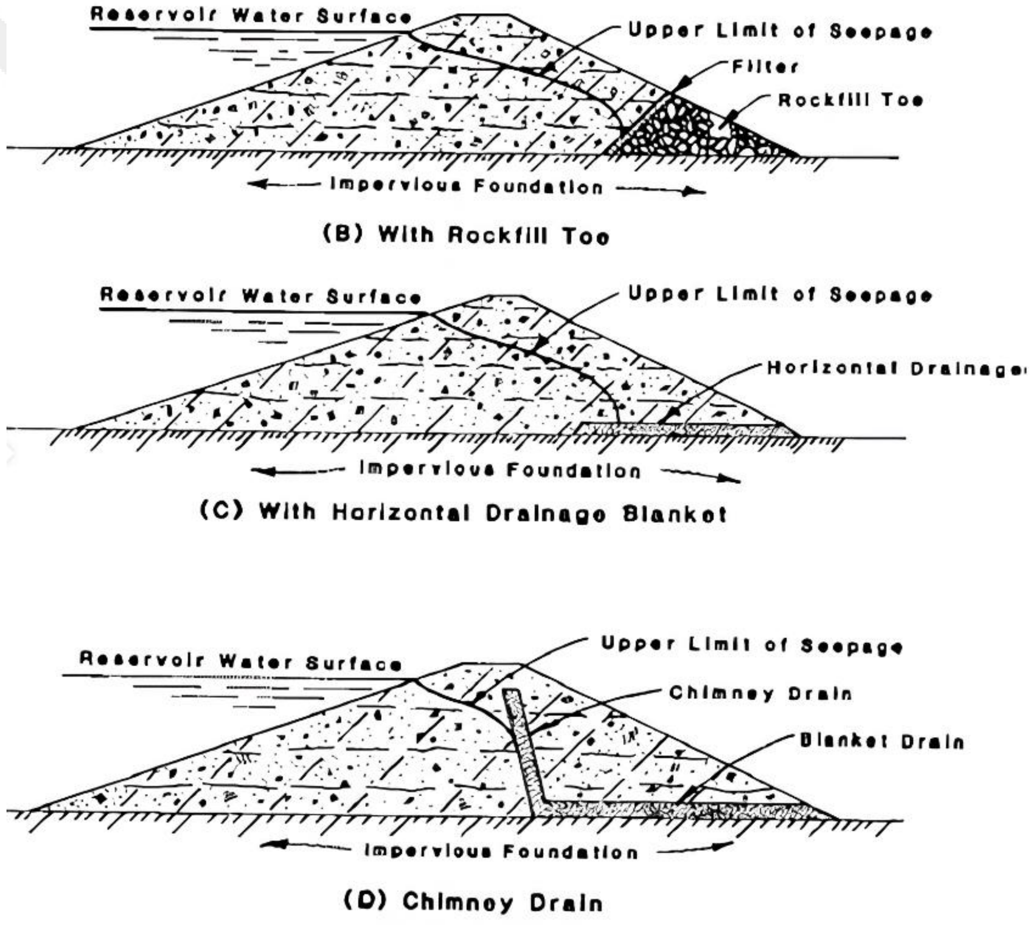


Figure 1.11. Drainage Types (USBR, 2012)

Toe drains are an essential component of embankment dam design, serving the purpose of collecting seepage from various sources and foundation seepage below the dam. They are most commonly constructed near the downstream toe of the embankment, although in some instances, they are placed under the downstream shell. However, this practice should be avoided as it requires the removal of the shell in case of repairs. The primary goal of toe drains is to reduce the hydrostatic pressure under the dam and downstream of the toe by intercepting the flow from seepage sources. A two-stage toe drain consisting of a perforated pipe surrounded by a gravel drain and a sand filter is considered the minimum necessary for an effective drain. Monitoring of embankment dams is critical as their performance changes with age, and monitoring using toe drains is an effective way to achieve this. Toe drains permit flow measurement, detection of cloudy seepage, and sediment accumulation, which are all essential features of a monitoring program. The type of toe drain configuration used depends on the expected seepage, with rectangular and trapezoidal cross-sections being the most commonly used geometries. (FEMA, 2011)

Blanket drains are an essential component in ensuring that the foundation of an embankment is protected from the risk of piping. These drains are designed to provide filter compatibility between foundation soils or bedrock that is not filter compatible with the overlying embankment. By doing so, they are able to prevent finer embankment soils from piping into underlying coarser foundation soils or bedrock with joints and fractures. Additionally, blanket drains can also protect foundation soils from piping into a coarser overlying embankment zone. Blankets are intended to collect foundation seepage and transmit any seepage collected by a chimney to the downstream toe drain. They are not intended to control the phreatic surface through the dam since the core material will have a higher horizontal permeability than vertical permeability due to the material being placed and compacted in horizontal lifts. In situations where seepage through the shell can come from a phreatic surface that is not adequately attenuated by the chimney or by the precipitation that can percolate through the shell, blanket drains play a critical role in protecting two seepage paths: one from the foundation and the other from the shell. To achieve this, the first stage filter is placed on the foundation to protect against soil erosion caused by seepage flow from the foundation into the downstream shell. Over that layer, the second stage gravel layer is placed that provides drainage of the collected water to the downstream toe of the dam. Over that, another first-stage filter is placed, which prevents erosion of the overlying shell into the blanket drain. In summary, a properly designed blanket drain is critical in ensuring the safety and stability of embankments and dams by mitigating the risk of piping and erosion caused by seepage flow. (FEMA, 2011)

Chimney filters play a crucial role in safeguarding an impervious core from potential internal erosion failures and simultaneously controlling the phreatic surface through the embankment. The use of a chimney drain is dependent on various factors, such as the expected seepage through the core, cracking potential, and composition of the downstream shell. If the downstream shell is coarser than the filter, a chimney drain will be required. In case rock fill is used for shell material, an additional zone or zones may be required between the chimney drain and the shell. These zones are usually referred to as transition zones, and the particle retention criteria should be met between these transition zones and the shell. Vertical and inclined geometries are commonly used for designing filter and chimney drains in an embankment dam. Although the vertical geometry is similar to a structure chimney, inclined geometries are also called chimneys. The type of geometry used is a function of the dam size, construction method, and core geometry, as described in the next sections. Vertical chimneys are used most often where the impervious core material is scarce and the downstream slope of the core is vertical. Inclined chimney filters and/or drains have the advantage of lessening the susceptibility of cracking at the impervious core-chimney interface and requiring a shorter horizontal blanket drain that results in a smaller quantity of blanket material. However, more difficulty is involved in maintaining proper location during construction since the chimney location must be moved laterally after placement of every lift. (FEMA, 2011)

1.4 The Purpose of the Study

The quantity of water that passes through the dam body due to permeability is known as the seepage, a crucial factor in ensuring the safety of dam construction. Filter systems have been developed to address the potential problems caused by seepage. These systems come in three main types: blanket, toe, and chimney filters, and they are essential for ensuring the safety of dam designs. The purpose of this study, therefore, is to develop design principles by analyzing the impact of various parameters on dams with different filter types. The main goal of this study is to establish design principles for filter systems.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

Soil consists of small soil particles stacked on top of one another of different shapes and types. There is a difference in size and shape between these soil particles. Based on the particle diameter of the soil, there are four main classes of soil: gravel greater than 2 mm, sand between 2.0 and 0.05 mm, silt between 0.05 and 0.002 mm, and clay less than 0.002. However, the soil is almost completely composed of soil particles. Thus, when classifying a ground, it is important to take into account the subspecies it contains heavily. Soils containing dense gravel and sand are called coarse-grained, and those containing silt and clay are called fine-grained soil. Even though these soil particles, which are of different sizes and shapes, are solid and formed as a whole, they also contain air, water, or space. Through the gaps between soil particles, water can flow. The soil property caused by this flow is called permeability, and this flow is called seepage.

It is also important to be aware of the saturation property of soils before proceeding. Soil saturation occurs when water fills the whole space between particles. A soil with these characteristics is referred to as saturated soil. The boundary line separating the saturated soil from the unsaturated part is called the phreatic surface. To make flow calculations, soil saturation must be taken into consideration. Because some soil particles such as clay and silt are in a water-holding structure.

In permeable soil, seepage can occur in two ways: steady or unsteady. An unsteady condition involves changes in the direction and velocity of the flow over time. A steady condition occurs when the velocity and direction of the flow are constant concerning time. Continuity equations or mass conservation laws are used when calculating flow in saturated soil. There are two possible assumptions for calculating seepage in the presence of phreatic surfaces. The first assumption is that the phreatic surface is a sharp boundary separating saturated soil from dry soil. It may be possible to obtain a flow model that complies with Darcy's law if the soil and the flow are assumed to be incompressible, in which case a Poisson or Laplace equation can be used to perform the analysis. This problem involves calculations involving unknown geometric boundaries, which are known as free boundary problems, and which provide the position of the phreatic surface. The second assumption is that the flow is continuous between the saturated region and the unsaturated region. Therefore, the phreatic surface cannot be considered as a flow boundary and instead, the soil boundaries are considered as flow boundaries. Accordingly, Richard's equation provides more accurate results for these assumptions (Mavroulidou, 1999).

2.2 Seepage

Fluid movement from the dam body, foundation, or surroundings is called seepage (Vick, 1983). All types of dams are susceptible to seepage or the danger of seepage. The seepage is caused by the potential head difference created by the water head difference in the upstream and downstream parts of the dam. Seepage varies proportionally depending on many different factors, including soil properties, type of fluid, type of dam, and even the geometric shape of the dam (Özer and Bromwell, 2012). It is a known fact that fill dams constructed from natural materials are prone to seepage as a result of the inherent properties of the materials used in their construction. And if this leak is not taken under control, many problems can be encountered (Khalid et al., 1990). In the case of excessive seepage, the pressure created by the water in a dam's body can cause the dam to become unstable. In addition, the leaked water may carry small soil particles that can cause internal erosion and piping, causing major hazards both to the dam and the surrounding environment (Arshad and Babar, 2014) (Moayed et al., 2012). Therefore it is imperative to understand flow theories and infiltration principles to understand the countermeasures to infiltration, which is a major threat to embankment dam safety.

The D’arcy formula, which emerged in 1856, became the foundation for studies of seepage. According to this law, the seepage rate of an incompressible fluid that flows through a homogeneous porous structure is equal to the multiplication of the D'arcy permeability coefficient, the hydraulic gradient, and the flow's cross-sectional area. Numerous experimental studies have been conducted to analyze the accuracy of this law and to develop principles for its practical application. Beresford and Clibborn were two of the names who contributed to broadening horizons through their experimental studies. Their studies, which are one of the earliest studies to understand the concept of internal erosion, contributed to understanding the importance of hydraulic gradient. The concept of the hydraulic gradient can be defined as the ratio between the energy lost between two points in the ground and the distance over which the loss occurred. In other words, it describes the amount of energy lost per unit of distance for each point in an aquifer. Reinforcing the importance of this concept, which is complementary to D'arcy's law, experimental studies show that concrete steps have been taken in seepage analysis.

Dupuit (1863) made assumptions about flow theory to simplify the solution of Darcy's equation. Based on his findings, it can be stated that the seepage lines of flow in an unconfined aquifer are horizontal for small slopes and that the hydraulic gradient is equal to the slope of the free surface, which does not change with depth. As the years indicated in 1886, Forchheimer proved Laplace's equations could be used to determine the distribution of water pressure and velocity in the seepage. Then, Karl Terzaghi (1922, 1925) drew attention to the pressure forces created by seepage and suggested that a filtration system should be designed (Smith, 1972). In 1937, Arthur Casagrande revealed that D'arcy's law and Laplace's equation are the fundamental formulas for seepage detection. It was also stated by Casagrande that the flow net method should be used to analyze the seepage in the dams (ICODS, 2015).

2.2.1 Seepage Analysis Methods

The development of seepage calculation began after the fundamental mechanisms of seepage flow were understood. Analytical methods were first used to perform these calculations. Nevertheless, these analytical methods can not be used for every flow type and condition. With certain limitations and assumptions, it can solve flow problems that occur in one or two-dimensional environments, which are generally homogenous and isotropic, and in structures that are simpler and more limited. The Casagrande method, one of the oldest and most well-known of these methods, proposes an analytical solution for calculating seepage, taking into account the downstream and upstream water heads, hydraulic gradient, and ground permeability. Dupuit presents his analytical method, arguing that discharge and phreatic lines are independent of the dam slope. In the equation he proposes to calculate seepage discharge, he takes into account the height of the upstream and downstream water, the seepage length, and the hydraulic conductivity parameters. Unlike the Dupuit formula, another approach that makes it possible to calculate seepage discharge without considering the water head is the Schaffernak and Van Iterson approach. In this approach, the seepage is calculated by the hydraulic conductivity, the horizontal length of the seepage surface in the dam body, and the angle of the water head downstream with the horizontal ground. There is a slight difference in Pavlovsky's treatment of the solution from the stated solutions and he develops two different seepage quantity equations depending on whether or not there is any water downstream. Groundwater and Seepage, published in 1962 by Harr, discusses these analytical approaches and several other approaches to calculating seepage rates. Changxi, on the other hand, developed an analytical method for the seepage calculation by assuming that the seepage in the blanket part of the embankment dam is linear. The foundation was considered to be permeable and the drag coefficient was determined by taking the average of the seepage discharge of the floor (G. Li et al., 2020). Using linear differential equations, Polubarinova-Kochina (1962) developed formulas that can be used to calculate the seepage height by assuming water in the downstream and upstream portions of a rectangular dam body. It is also possible to calculate the seepage using a quasi-steady state analytical method, which assumes a constant phreatic surface at every moment (Bear, 1792). In the 1960s, with the development of methods for solving complex differential equations for seepage analysis, the demand for analytical seepage calculation methods began to decline. However, there are analytical methods developed in recent history (Rezk and Senoon, 2011; Kacimov et al., 2019; Deng et al., 2018; G. Li et al., 2020).

The biggest revolution in seepage calculations was with the introduction of the finite difference method. It is a numerical solution method that is capable of solving all problems that can be studied using conventional analysis methods, including those involving heterogeneous soils that are not suitable for conventional methods (Rushton and Redshaw, 1979). It uses Laplace's equation to determine the two-dimensional steady-state bounded flow through the soil (Budhu, 2007). It was first used in seepage analysis in the pre-computer era by Richardson in 1911 to solve steady-state seepage problems. Finite difference analysis is a method that attempts to understand the whole from the parts by separating the parts of a structure into subparts and analyzing the effect intended on each part. The area where the seepage is investigated is divided into grids and a finite difference method and differential equation are defined for each grid. The analysis of the structure is made by considering the solution of all grids one by one and the boundary conditions with each other. Bardet and Tobita (2002) analyzed several free surface seepage problems to explain the finite difference method with numerical techniques. The results of the study showed that it is a practical method for analyzing many seepage problems. Using the finite difference method, Benmeberek et al. (2005) numerically investigated the failure of sand-soil seepage in a cofferdam. Kermani and Barani (2012) used the five-point approximation technique and the finite difference method (FDM) to analyze seepage in an earth dam built on impermeable, homogeneous, and isotropic ground. Based on the results of the study, it was shown that the finite difference method could be successfully utilized for the analysis of seepage from an isotropic and homogeneous earth dam.

A major contributor to the growth of numerical models was the use of digital computers in the 1960s. Methods such as the finite difference model, which was formerly used to accompany analytical methods, are now able to analyze more complex structures in greater detail through computers. In addition to the finite difference method, two more methods used in calculations were developed: the finite element method and the boundary element method. The finite difference model was the most widely used and the analyses were initially made with this method (Remson et al., 1971). The difference between the finite element method from the finite difference method was that it allowed the area to be examined to be divided into sub-areas of different sizes and shapes. These two methods are used successfully in the solution of seepage problems. Neumann and Witherspoon (1970) introduced the finite element method (FEM) for a steady state free surface state. To analyze seepage using the Finite Element Method, three steps must be followed: Physical idealization, formulating equations, developing computer programs, and checking their validity (Mukhopadhyay, 2008). The finite Elements Method is a satisfactory method that has been used for a long time to explain low-cost, high-efficiency, and reliable seepage modelling (Zhongru et al., 2002). Li and Desai (1983) used FEM to perform seepage and stress analysis in the embankment dams. And compared the results with field observations. Gan et al. (1999) compared the current seepage measurements of the Mardi dam, one of the embankment dams in Austria, with the data obtained by FEM.

They tried to analyze the effect on the flow rate and the height of the piezometer by modifying the permeability numbers. They discovered that the results were in agreement with the calculations. Çalamak et al. (2018) analyzed the steady-state seepage in a homogeneous embankment dam in terms of different sizes and material properties for different types of filters by using the finite element method.

Another method is the boundary element (BEM) method introduced by Liggett (1977). This method allows us to obtain information about different boundary points without solving the whole problem by developing discrete equations for different points on the free surface. It is less common than other methods to use the boundary element method for seepage analysis. Chang (1988) used the laboratory model and boundary elemental method as numerical analysis to determine the free surface behavior and position during drawdown and steady-state conditions. In the study, steady-state and non-steady-state calculations of unconfined seepage were compared. Beer and Duenser (2019) examined seepage flow in several different environments, including confined and unconfined problems in isotropic and anisotropic media, and attempted to demonstrate that this method has greater accuracy than other numerical methods and is more capable of obtaining accurate results with fewer unknowns than other numerical methods.

For temporary seepage conditions, there is a need for a more effective method than those described above. The Boundary Fitted Coordination (BFC) method makes it possible to create grids with irregular boundaries. It can be adapted and used for both continuous and temporary seepage problems (Hartono, 2002). Graphical methods have been suggested as a method for predicting seepage from a reservoir under free-surface stationary conditions by Cedergren (1977). Hutchison (1983) demonstrated that programmable calculation methods based on Darcy's law, Dupuit's assumption, and Bear's hydraulic approach can be used to calculate seepage rates in earth dams.

There are several advantages and disadvantages associated with each of these methods used in seepage analysis. It is generally preferred to use finite differences for homogeneous and limited media, for example. Programming the finite element method is easier, it is capable of solving complex limited structures, and it can solve anisotropic or heterogeneous media more effectively than other methods. Sometimes these methods can be evaluated most advantageously when used together.

(Mavroulidou, 1999) As a result, there are many different seepage analysis methods in the literature, and the method to be used should be selected based on the characteristics of the problem. In the following sections, detailed information about the study's methodology will be presented.

2.2.2 Seepage Analysis Software

To perform seepage analysis, first, a mathematical model must be developed. The mathematical model consists of differential equations and given conditions, which are simplified by assumptions. An analytical method is developed to solve the physical problem consisting of differential equations. Although generating analytical solutions may be challenging because of the irregularity of a region in which boundaries cannot be defined, the presence of a variety of materials that cannot be simplified using mathematical expressions, and the inability to form a simple equation for anisotropic environments, generating analytical solutions may not be as straightforward. In cases in which the analytical method is not possible, numerical methods are used to obtain approximate results. In these numerical methods, a large number of equations are generated that are too complex to be solved manually. For this reason, computer software using the infrastructure of these methods has been developed (Abhilasha and Balan, 2014). There are many popular programs in this category, including SEEP/W, ABAQUS, PLAXIS, MODFLOW, ANSYS, PDEease2D, SVFLUX, DIANE, SLIDE2, and GEO5.

Thieu et al. (2000) used PDEase2D to solve steady-state and transient seepage problems along earthen dams. Kamaratih et al. (2022) used Bishop and Janbu Limit Equilibrium Methods to analyze the transient seepage and slope stability of an earth-fill dam which had been modelled in the laboratory using Slide2D software. They conducted the research using different sizes of sand and ground material. In comparing the results of the laboratory experiment with the numerical calculation, it was determined that both provided relatively similar results. Batelaan and Smedt (2005) stated that drainage simulation in groundwater flow can be calculated with MODFLOW's DRAIN package when the drainage level is considered equal to the topography. However, they suggested a SEEPAGE package for MODFLOW, saying that conceptual and practical errors occur due to reasons such as the water head above the topography, and parameterization of conductivity. In the study, it was stated that the results obtained with the SEEPAGE package were more accurate. Kacimov et al. (2019) performed the seepage simulation of an embankment dam with a clay core toe drainage system with MODFLOW using the hodograph method.

AlJairry (2010) used CivilFEM/ANSYS software to analyze two-dimensional steady-state seepage from a two-zoned embankment dam on an impermeable foundation. By changing the permeability coefficients, the seepage was examined and it was concluded that this permeability change in the layers had an intense effect on the amount and velocity of seepage. Based on the results of ANSYS software, Ma et al. (2012) analyzed the seepage and stability of a tailings dam in Yunnan province and concluded that the results could be used for hazard assessment. Li et al. (2018) mention that programs such as Geo-Studio can be used to calculate unsaturated soils in two-dimensional stability and seepage. As mentioned in the study, which pointed out the limitations of modelling programs that can be used to perform three-dimensional calculations, seepage, and deformation analysis with ANSYS software were conducted, and the results were compared with those obtained with Geo-Studio.

Lü et al. (2018) preferred ABAQUS software to calculate seepage and stress analysis in the foundation and body of the concrete gravity dam. It has been determined that the effect of the seepage on the stress is reflected in the seepage force. Taking into account the seepage in the foundation of the dam, it has been determined that if the dam body is considered permeable, the seepage will have no impact on the uplift force, whereas, in an impermeable body structure, the seepage will cause the uplift force. In their study, Li et. al. (2019), simulated a clay core embankment dam using ABAQUS software. They analyzed the behavior of the dam in saturated and unsaturated conditions and compared the results with the values obtained from the Geo-Studio software. The results are mutually supportive.

For the analysis of dams in this study, PLAXIS 2D and SEEP/W were used. It was considered important that many studies had been conducted in the literature before choosing these two programs. It will be discussed in greater detail in the following sections of the thesis, including the working principles of these programs, basic equations, and their history, but for now, it may suffice to review the seepage analysis studies published in the literature.

Sari et al.(2017) used PLAXIS to analyze the safety of the Sermo Dam, one of many fill dams in Indonesia, under seepage conditions and compared it with data from piezometer and V-Notch monitoring. Their results were that the height of the reservoir increases the pore pressure and seepage, which affects settlement. Alateya and Asr (2018) studied the potential for cavities from seepage in dams to cause damage to dams. Using PLAXIS 2D software in this study, the researchers concluded that these cavities significantly increase seepage, especially when the flow rate increases and that horizontal mobility of the cavities is more effective than vertical mobility. Bayat et al. (2019) took samples from the downstream drainage of a dam at 15-day intervals for 1 year and compared these sample data with the transient seepage modelling they performed with PLAXIS 3D. From here, they obtained the seepage in the event of a potential failure due to erosion or piping in the dam with a very reliable accuracy value. Zewdu (2021), on the other hand, preferred PLAXIS simulation to analyze the seepage reliability of the Ribb Dam. Based on an analysis of seepage data obtained following standards such as the United States Army Corps of Engineers (USACE), the British Dam Society (BDS), and the Canadian Dam Association (CDA), the dam was found to be reliable. Unlike other studies, Sharma and Manna (2021) examined the failure analysis of a hypothetical dam, which consists of fine sand and whose upstream face is covered with geomembrane and brick, with PLAXIS and GeoStudio software. A series of results were presented, including possible causes of failure and solutions.

Soleymani and Akhtarpur (2011) performed a two-dimensional seepage analysis with and without the cutoff of the Shurijeh Dam in Iran with SEEP/W. Another study in which existing dams were analyzed with SEEP/W was carried out by Yarahmadi et al (2014). In the study, seepage data from Shian and Khan-Abad Dams were collected and then compared with data from 2D and 3D dams modelled in software. A large difference was observed between field data and modelling, and the reasons why this occurred were discussed. Khazaei and Asadi (2014) compared the pore pressure head data of the Kamal Saleh earth dam during the ten-month construction and impoundment process with the models they created with SEEP/W 2D and SEEP/W 3D software. It was stated in the study that there was a difference between 6% and 23% between them and that the 3D version provided more realistic results for seepage modelling. Seepage modelling of the Hub Dam in Pakistan was also done with SEEP/W. (Arshad and Babar, 2014) Based on the results of the study, we can conclude that the data obtained in the study are well in agreement with those obtained in the field, and the dam is at a level of safety that will allow it to withstand any possible seepage conditions. Kirra et al. (2015) performed the seepage and security analysis of the Mandali Dam in Iraq with this software. The state of the dam before the reservoir fills during construction, the steady state seepage condition, and the behavior of the dam in the case of rapid drawdown in the reservoir were investigated using the Ordinary Method of Slices, Bishop, Janbu and Morgenstern and Price methods. The reliability of the dam has been verified and the most dangerous situation has been determined to be the rapid drawdown. Çalamak et al. (2017) investigated the uncertainty of hydraulic conductivity and Van Genuchten parameters with SEEP/W modelling on unsaturated fill dams with transient seepage. In this study, in which the Monte Carlo method is used for probabilistic analyses, the seepage rates in different embankment dams are evaluated probabilistically and the degree of uncertainty is tried to be estimated. It was concluded that seepage followed the generalized extreme value or three-parameter lognormal distribution. Another study investigated the response of a clay core embankment dam to varying slopes in the embankment and core. Leak results from ANN and SEEP/W were compared and found to be very similar (Jamel, 2018). Zedan et al. (2018) used SLOPE/W and SEEP/W software to calculate slope safety under drawdown conditions of the Khasa-Chai Dam. Rapid and slow drawdown conditions were simulated and safety coefficients were calculated for both cases. It was determined that the phreatic line level remained the same in both cases and the dam was reliable in both cases. In another study, the effects of core permeability, core width, core base thickness, core penetration on seepage, pressure head, exit gradient, and upstream and downstream slope stability were experimentally and numerically modelled on earth dams with and without a core. A comparison of the results obtained from SEEP/W and the experimental model was conducted, and they were found to be correlated. It was determined that the decrease in core permeability, increase in core thickness, and increase in upstream and downstream slope ratio (H/V) reduced the seepage ratio (Salem et al., 2019). Jassam and Abdulrazzaq (2019) performed seepage analyses of homogeneous and inhomogeneous dams with SEEP/W. It was concluded that the number of seepage increases with the ratio of height water upstream to length water, with saturated soils experiencing the highest level of seepage.

When the studies are examined, it can be concluded that the software used for seepage analysis in general gives more accurate results in analyses made on dams with a simpler design and fewer external variables. Although three-dimensional analysis of a dam is more beneficial, two-dimensional analyses are commonly used for a variety of reasons, including the assumption that the cross-section of a dam is continuous, and the necessity of using complex mathematical equations and modelling for complex and unique systems resulting from three-dimensional modelling. Upon reviewing the literature, it is apparent that no study provides a comprehensive understanding of the deviation values between the programs over the dam to be modelled in each of these programs. Nevertheless, SEEP/W and PLAXIS have been used together or in incoordination in several studies and have yielded similar results. In this study, these two software will be used in coordination.

2.3 Filters and Drains

It is not possible to draw a definite limitation on the history of the use of filters in dams. It is nevertheless possible to examine the literature to find out how filtering systems have become increasingly important in dams. Terzaghi carried out a series of laboratory studies on understanding the concept of erosion in the soil in 1919-1921. These laboratory studies show that a certain slope limit must be exceeded for erosion to occur. One of the conclusions of this study was that the use of another soil layer, namely filters, to prevent the internal movement of soil particles can avoid this problem. It was not until 1931 when the Bou-Hanifia Dam was constructed, that the practical application of the information obtained at the point of the filtration system became possible. This dam, sitting on the rock foundation, had a five-layer filter that ran through the fine sand to the rock. Even though the filter in the dam provided the Terzaghi equation, the grain size in the layers was determined through experimental studies.

In 1934, Harza expressed views on drainage systems in dams and suggested precautions to be taken against flotation at the dam toe. Then Terzaghi published his equation for the determination of grain size in 1939. Bertram analyzed the dimensional distribution of soil particles for use as a filter material and confirmed that the Terzaghi equation gives reliable results in 1940. USACEs conducted a series of studies on dam design and published design criteria (USACE, 1941; USACE, 1942; USACE, 1953).

The Bureau of Reclamation published filter design criteria that were later found to be faulty and deprecated (USBR, 1947, USBR 1955). However, these studies revolved mainly around the sand. Kassif et al. (1965) demonstrated that the filter systems of clays behave differently from sand because clays are characterized by electrochemical bonds with different plasticity.

In 1982, the concept of the "perfect filter" was introduced. Vaughan, who came up with this concept, promised to prevent the movement of even the smallest particles that could be mobilized in the dam due to seepage with the perfect filter. Vaughan and Soares (1982) determined that after internal erosion had developed in the clay core of the Balderhead dam, the dam's filter was insufficient to retain small soil particles. They conducted a series of experiments to determine new filter criteria to prevent internal erosion in clay core dams and decided that the grading element is more important in the design than the permeability of the filter. Arulandan and Perry (1983) claimed that sand-gravel filters developed in the Terzaghi criteria do not consider the erodible character of the core material and the cracking potential of the filters, and this causes failure in many dams. They suggested that a series of studies be conducted to determine the percentage of particle dispersion smaller than the #200 sieve size and to measure erosion potential.

Sherard published "Basic Properties of Sand and Gravel Filters" in 1984. This study discovered that the fine-grained soil particles in the filters were found more loosely in the sections between the coarse-grained soil particles and they had a movement in this direction. The International Committee on Large Dams published the principles of filter design in "Bulletin 95" in 1994. It was focused on the stability and particle sizing of the ground material to be used in filter design. Later, Foster et al. (2001) after testing the reliability of previous studies, classified filter operation and gave detailed recommendations on the filter design of constructed dams and existing dams.

Milligan came up with a slightly different view in the field of filter design and suggested that a narrow-graded filter design would be more appropriate than a wide-graded filter design (FEMA, 2011). Indraratna and Raut (2006) have proposed an analytical approach for analyzing particle size in a self-filtering layer ineffective filter designs, where erodible particles are carried and the filter functions as a self-filtering layer. This model, which has been tested in laboratory studies, has provided an alternative design approach to the limitations of conventional particle criteria.

On one hand, studies have been conducted to analyze the characteristics of the filter material used in the earth-fill dam, such as its type and grain size, but on the other hand, studies have been conducted to study the effect of the filters. Patel et al. (1964) conducted a study on understanding the effect of inclined filters on embankment dams and proposed a scheme that could be used in the design of earth dams. Moayeri (1972) investigated the seepage behavior of toe-drain dams with different slopes upstream. Study results, consisting of angles of 15, 30, 45, 50, and 90 degrees analyzed between the upstream and the horizontal, have been presented as graphs showing the seepage and the length of the drain, and compared with those of other studies. Mishra and Parida (2006) determined the required toe drain height for a homogeneous dam built on an impermeable foundation using Kozeyn's analytical formula. Rezk and Senoon (2012) tried to calculate the seepage analysis of an embankment dam with an upstream blanket using analytical solutions. Comparing the validity of their results with experimental data from another study, they found that the difference in head loss due to a blanket was 25% different.

Using Complex Function Theory, Rezk and Elela (2015) calculated the minimum trapezoidal filter height in dams. The minimum filter height was calculated for different dams by changing parameters such as the water head in the dam, the angle of the filter with the horizontal ground, and the length of the upstream surface of the filter. As a result of comparing the results obtained from the present study with those obtained from the Hathoot and Kozeyn formulas, it was determined that the filter height obtained from the present study was higher than that obtained from the two formulas and that the phreatic surface was lower. By using both the physical and analytical models of a dam with a height of 30 meters, a top width of 10 meters, and a slope factor of 1.5, Aboelala (2016) analyzed the seepage situation in the dam under different seepage control methods such as toe drainage systems and a catch drain. The results, presented in the form of graphs, revealed that different leak control methods are highly effective at the seepage rate. By incorporating different drainage types, blank, toe, and chimney in the design of the filters, Çalamak et al. (2018) attempted to assess the effect of physical and material properties on seepage and phreatic line. In this study, in which the numerical method is used, steady-state seepage calculation was made on a homogeneous and simple zoned earthen dam. According to the results obtained, if the blanket filter length increases, the seepage increases, and the phreatic line becomes shorter; toe filter height increases seepage; if the grain size of the material used in the chimney filter increases, the phreatic line rises to a steeper position in the core. Li et al. (2020) analyzed the seepage flux of a rockfill dam with a blanket filter with a simplified analytical method based on Darcy's Law. A comparison was conducted between the data they obtained from the analytical method and the data obtained from the numerical method and it was determined that there was a lower error rate than 10%. Kumar et al. (2022) performed seepage analysis on 21 different dam models with and without filters, consisting of different widths of impermeable cores designed on an impermeable foundation. The obtained results showed that increasing the dam's height, filter length, downstream slope, and longitudinal slope increased seepage discharge.

Many studies using different methods for seepage analysis in filtered systems (Bennett, 1946; Uginchus, 1966; Changxi, 1963; Baozhong, 1981; Hussain et al., 2007; Yoshitake et al., 2012; G. Li et al., 2020). A detailed description of these methods will not be provided in this study, and information about the subject will not be distributed. Because, apart from analytical methods, many methods used for seepage analysis can also be used in the analysis of drained systems. In this study, it was stated that the finite elementary method-based SEEP/W software would be used. A review of previous studies in this field will be useful in understanding the performance of the software in the seepage analysis of filtered dams.

A study conducted by Moharrami et al. (2014) evaluated the horizontal drain as a method of preventing the increase in pore water pressure in the earth-fill dam under rapid drawdown conditions. The effects of drains of different sizes, numbers, and locations on slope stability and seepage were investigated and these models were made with SEEP/W and SLOPE/W. In the study conducted on ten different scenarios, it was concluded that drainage reduces the pore pressure, the increase in the number of horizontal drains increases the slope stability, and the drain length has no effect after a certain length. Mansuri and Salmasi (2013) investigated the effect of the cutoff and blanket filters on seepage in embankment dams with their modelling on SEEP/W.

They concluded that in these models in which drain lengths and cutoff depths are varied, the increase in drain length increases the seepage, and the central cutoff is the most ideal situation in terms of seepage.

Performing seepage analysis on an embankment dam with horizontal toe drainage, Irzooki (2016) calculated the seepage variation for different upstream and downstream slopes, different drain lengths, and different dam heights and widths. In this study, SEEP/W and Artificial Neural Network (ANN) analyses were used to analyze the seepage data, and it was determined that the slope increased the seepage, as did the height upstream of the drain and the length of the drain, and the length of the drain was the most influential factor in the seepage increase. It has been determined that the empirical equation developed in the study to calculate seepage gives very similar results to the numerical calculations. Suleimany and Mamand (2020) modelled 972 homogeneous embankment dams with two different upstream and downstream slopes of the dam and three different values for each: dam height, filter length, permeability coefficient, freeboard, and top width using SEEP/W, Slide, and ANN. The increase in the slope and the increase in the length of the drain increased the seepage. Data obtained from ANN were compared with SEEP/W and Slide, and error percentages were determined as 1.5% and 9%, respectively. In terms of results, this study supports the results of Irzooki's study. Again, Refaiy et al. (2021) tried to understand the effect of drainage on seepage by modelling a 7.5 m high homogeneous embankment dam with different drainage types both numerically and experimentally. Analyses conducted with different lengths and angles of the drain were conducted to determine whether the angle and height of the drain with the horizontal had any effect on the seepage and whether the length of the drain increased the seepage. Furthermore, the results from SEEP/W and experimental tests are in agreement, and SEEP/W software seems to provide very realistic results for the analysis of seepage in homogeneous dams.

As a result, the fact that numerous studies on the analysis of seepage in filter dam systems are in agreement with each other, as well as the results obtained from experimental studies, confirms the reliability of the method used in this study. It is acknowledged that there are similar studies in the literature that analyze the effect of drainage systems on seepage, but there is a lack of a comprehensive study that analyses the impact of multiple parameters on the drainage system at the same time. A further step of this study, which was developed to eliminate this deficiency, will be the explanation of the methodology of the study, a series of questions ranging from the dam design to the selection of materials, the parameters of which varied dams were designed, and the specific working principles of the SEEP/W and PLAXIS 2D software used during the analysis.

CHAPTER 3
THE METHODOLOGY

The reasons for the necessity of performing seepage analysis for the safety of an embankment dam were explained earlier in this study. In the analysis of the concept of seepage, developments and studies from the beginning to the present were examined and information was given about the methods used in this field. The methods described in the previous sections are generally applied to dams that were designed, the material properties used were specified, the ground was assumed impermeable, or the dams were hypothetically designed for the study to be performed. It is important to note that all of these methods entail several assumptions, which makes it easier to analyze the concept of seepage, which is more difficult to analyze in practice. However, since soil permeability varies even within a short distance in a real structure, seepage causes partial changes in the structure over time due to changes in temperature, etc., the concept of seepage is more complex, and seepage monitoring methods in existing structures are more preferred as they provide simultaneous information. The objective of these and similar studies is to establish a baseline by developing simulations for the construction of a reliable dam rather than performing seepage analyses on existing dams, which would serve as a basis for developing preventive systems, and understanding the behavior of the seepage within the dam in advance. Using this principle as a foundation, this part of the study will provide a comprehensive analysis of all of the methods previously described chronologically. It will provide detailed information about the methods and software used in the study, as well as the stages of designing the embankment dam intended for the study, as well as the parameters used in developing the 273 dams to be analyzed in the study.

3.1 Seepage Calculation Methods

Seepage calculation methods are used to determine the effect of seepage on a dam and to find potential seepage pathways. The calculation technic that is going to be used in analyses must be methodical, logical, and realistic. Seepage analysis must be repeated using different calculation methods to be sure of the accuracy of the results. There are several methods are available for determining the seepage rate in an embankment dam. Four widely used analytical methods are:

- Analytical Solutions
- Physical Solutions
- Graphical Solutions
- Numerical Solutions

Analytical methods are methods used to model and analyze flows with simple geometry that occurs in one- or two-dimensional homogeneous and isotropic media. They consist of simple or complex differential equations that describe the flow. The basis of analytical methods in terms of the seepage concept was established with the Darcy equation, and later on, many names developed their equations to analyze seepage in the models they determined under certain limitations. For detailed information about these names, Chapter 2 can be examined. These methods are preferred for several reasons, including their low cost, the fact that they can be used as a quick information acquisition tool rather than a detailed analysis, and their ability to simplify complex systems and provide a better understanding. Nevertheless, it is mostly applicable to limited situations, and it fails to produce realistic results since it disregards a variety of environmental factors. Additionally, it fails to provide accurate results in inhomogeneous anisotropic systems or has a high margin of error, leading us to investigate alternative seepage analysis methods.

The physical solution is a method of analyzing a structure based on measurement and observations, where virtual laboratory conditions are created by scaling the structure being analyzed. As a result of their ability to simulate field conditions and analyze structures that cannot be modelled analytically, physical models are valuable. The reasons such as the time and financial cost of producing a large number of models, and the possibility of human-induced errors while simulating the conditions to produce misleading results reduce the attractiveness of this method.

Graphical solutions are methods that emerge from visualizing and solving mathematical equations. The most well-known of these is the flow net method, which is based on the Laplace equation. Flow lines represent the path followed by seepage, and equipotential lines drawn perpendicular to it are the lines along which the energy available to induce flow is the same. After the flow nets have been determined, the equation given in Figure 3.1 can be used to calculate the seepage. It is advantageous to use this method because it is low-cost. However, it requires a considerable amount of time to draw flow nets, and achieving a realistic result depends on the ability to draw flow nets. Even though the graphical, physical, and analytical solutions each have advantages and disadvantages in terms of their uses, they are insufficient for a study such as this in which comprehensive analyses are required. Therefore, this study was carried out using numerical solution methods to meet the requirements of this study.

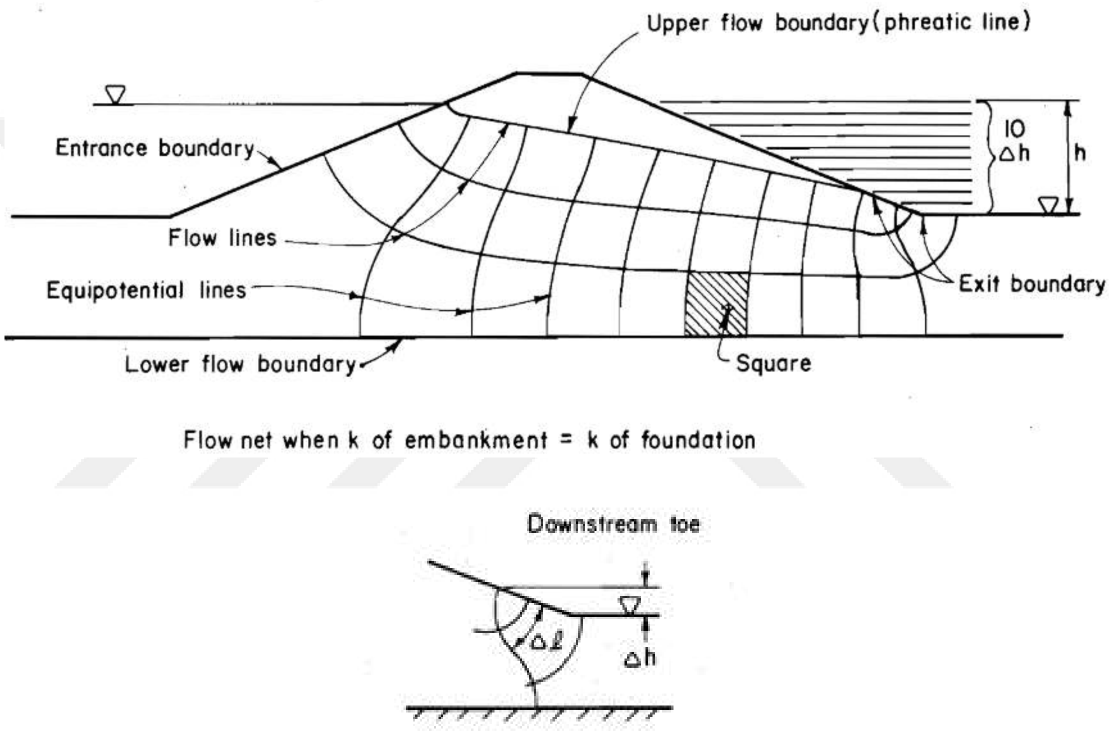


Figure 3.1. Flow Net Construction in an Embankment Dam (NRSC, 1979)

Rate of discharge $$q = kh\xi \tag{3.1}$$

Discharge gradient $$i_d = \Delta h/\Delta l \tag{3.2}$$

Rate of discharge $$p_s = \gamma_w \imath_d \tag{3.3}$$

Seepage pressure $$Q= ql \tag{3.4}$$

h = head of water (upstream water surface minus downstream water surface)

Δh = head increment between equipotential lines = h/N_d

k = permeability coefficient

N_d = number of equipotential lines (drops) in flow net

N_f = number of flow channels in a flow net

ξ = shape factor $=N_f/N_d$

L = total structure length normal to the section represented by the flow net cross-section

Δl = flow path length across a square of discharge face

3.1.1 Numerical Analysis Methods

It is possible to analyze simple flow conditions with the methods described earlier. It is important to note, however, that as the complexity of the system increases, the equations resulting in it increase and problems arise that cannot be solved manually. Numerical methods are used to analyze these complex problems. Some reasons why numerical methods are preferred:

- Ability to model two or three-dimensional problems with complex geometry or layers,
- Giving more realistic results as it offers the opportunity to model different material properties,
- Modelling of transient or time-dependent flow is possible,
- As well as being easy to access, it is also cost-effective.

The Finite Element Method is the numerical analysis method that forms the basis of the analyses in this study. The basic working principle is to divide the flow region into meshes as shown in Figure 3.2. The discrete elements divided by these meshes, which have different shapes, form N equations and N unknowns, connected by nodal points. Following the determination of material properties (permeability, void ratio), boundary conditions (flow rates, heads) are determined. The solution of the differential equations written for each node can be done separately and the behavior in the main structure can be analyzed approximately. (USACE, 1986)

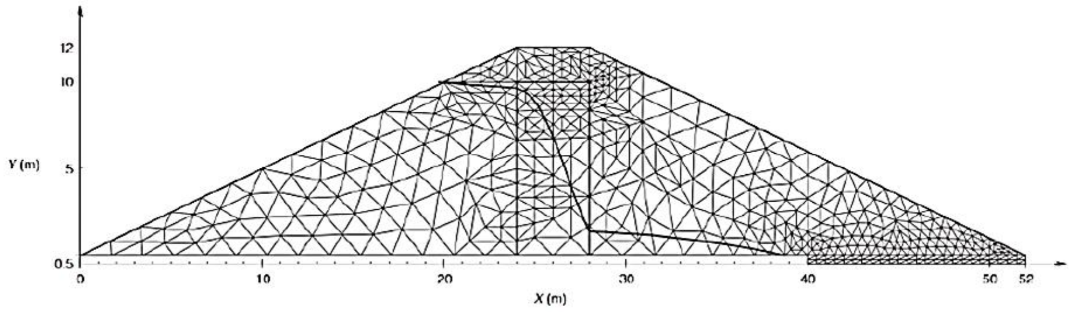


Figure 3.2. An embankment dam divided into the mesh of FEM (Xu, 2019)

This study utilized two FEM-based software due to their advantages. PLAXIS 2D software was used to examine the reliability of the design of a homogeneous dam, which will serve as the basis for 273 different dams. A total of 273 dams were designed to be analyzed for seepage and using SEEP/W, the seepage and the water head in five different sections of the dams were determined.

3.1.1.1 Plaxis 2D

Plaxis is a software built on the finite element method and it uses this method to analyze deformation and stability in geotechnical engineering mechanics. The history of Plaxis began in 1987 at Delft University of Technology to analyze river embankments on the soft soils of Holland. Plaxis company was established in 1993 and the first Plaxis 2D for Windows was released in 1998. Plaxis 3D, Plaxis Suite, Plaxis 2D Dynamics, Plaxis 2D Thermal, Plaxis 2D Plaxis Plaxflow, Plaxis 3D Dynamics, etc..versions were developed. Plaxis 2D gives opportunity users to analyze layered soils, hydrostatic pore pressures, non-linear and anisotropic behavior of soils, and settlements in soils depending on the time, seepage, slope stability, dynamic analysis, and fast water drop in the reservoir. Plaxis 2D is preferred for practical interface, soil description option, time-dependent results, and deformation analysis opportunity. (BENTLEY, 2023)

3.1.1.2 SEEP/W

GeoStudio software was founded in 1977 and SEEP/W was incorporated as a sub-software within GeoStudio. A geotechnical analysis tool called GeoStudio analyzes slope stability, heat and mass transfer, and groundwater flow. The software used in this study SEEP/W is a powerful finite element software product for modeling groundwater flow in porous media. SEEP/W can model simple saturated steady-state problems or sophisticated saturated/unsaturated transient analyses with atmospheric coupling at the ground surface. The software selection was based on the advantages of the software. In the literature, several studies used SEEP/W software to analyze seepage in an embankment dam. The foundation of the SEEP/W software is predicated on Darcy's law, Laplace equation, total head formula, and Finite Element Equations, which have already been used for accurate calculation and prediction of seepage widely.

3.2 Dam Design and Stability Analysis

Dam design is a challenging study, that necessitates a field investigation, a laboratory analysis, analysis results in exposition, determination of exact dam situation, dam type selection, dam material selection, and dam design with all these parameters before construction. All these detailed processes make a dam design period as long as more than five years and many experts are involved in these design processes. Nevertheless, since the purpose of this study was to determine the effect of filter systems on seepage in earth-fill dams rather than to design a dam, the design processes were different from those typically used and were carried out for the purpose of the study. In order to design the main dam for this study, three basic steps were followed:

1. Identifying the materials and parameters to be used in the dam.
2. Determine the optimum dam section with the desired height, taking into account the properties of the materials.
3. Performing stability analysis with Plaxis 2D after determining the dam section.

3.2.1 Material Selection

Embankment dams can be constructed with a combination of many materials, including soil, rock, asphalt, concrete, and geosynthetic materials. For the purpose of reducing costs, most embankments of constructed earth-fill dams are built utilizing local materials. In this study, inorganic materials to be used in the dam's embankment, core, and filter section are divided into two main categories in terms of engineering: fine-grained soils and coarse-grained soils. Fine-grained soils are generally used in homogeneous dams and impermeable cores of zoned embankment dams, while coarse-grained soils are used in the embankment and filter parts of zoned earth-fill dams (USSD, 2011). It was necessary to make both homogeneous and core dam designs in this study because the dams analyzed in this study have different filter types (blanket, toe, and chimney). In the first step of the design, the type of soil to be used in the body, drainage system, and core of these homogeneous and zoned dams to be designed should be determined.

As a basis for determining soil types for dam design, Table 3.1 was used as a guide. The table was created by analyzing samples from 17 American states between June 1, 1960, and December 1985. In this table, the material type and general properties are listed. By examining the strengths and weaknesses of the materials and evaluating the basic information about the dam materials, clayey gravel (GC) as the filling material, clayey sand (SC) as the core material, and sand (SW) as the filter material were determined. Some properties of these materials should be known in order to define them in Plaxis 2D and SEEP/W software: unsaturated unit weight (γ_{unsat}), saturated unit weight $(\gamma_{sat,})$, permeability (k), modulus of elasticity $(E_{ref,})$, Poisson ratio (v_{nu}), cohesion (c_{ref}), angle of friction $(\varphi_{ph,})$, optimum water content (WC_{opt}), specific gravity (SG), void ratio (e), saturated water content (WC_{sat}), and compressibility. More than one method and formula were used to determine the specified parameters of these materials. Ranges of $\gamma_{unsat}, \gamma_{sat}, c, \varphi, WC$ parameters in certain soil types were determined using Table 3.2, Table 3.3, and Table 3.4.

Table 3.1. The weak and strong properties of materials (USBR, 1990)

Soil group name	Group symbol	Permeability	Shear strength (saturated)	Compressibility (saturated)	Workability as a construction material
Well-graded gravel	GW	Pervious	Excellent	Negligible	Excellent
Poorly-graded gravel	GP	Pervious	Good	Negligible	Good
Silty Gravel	GM	Semi-pervious to impervious	Good	Negligible	Good
Clayey Gravel	GC	Impervious	Good to fair	Very low	Good
Well-graded sand	SW	Pervious	Excellent	Negligible	Excellent
Silty sands	SP	Pervious	Good	Very low	Fair
Clayey sand	SM	Semi-pervious to impervious	Good	Low	Fair
Silt	SC	Impervious	Good to fair	Low to medium	Good
Lean clay	ML	Semi-pervious to impervious	Fair	Medium	Fair
Organic silt and organic clay	CL	Impervious	Fair	Medium	Good
Elastic silt	OL	Semi-pervious to impervious	Poor	Medium to High	Fair
Basic silt	MH	Semi-pervious to impervious	Fair to poor	High	Poor
Fat clay	CH	Impervious	Poor	High	Poor
Organic silt and organic clay	OH	Impervious	Poor	High	Poor
Peat and other highly organic soils	PT	-	-	-	-

Table 3.2. Density Value Ranges of Soils (Lindeburg, 1986)

class group symbol	description	range of maximum dry densities (ibm/ft^3)	range of optimum moisture content %
GW	well-graded, clean gravels, gravel-sand mixtures	125-135	11-8
GP	poorly graded clean gravels, gravel-sand mixtures	115-125	14-11
GM	silty gravels, poorly graded gravel-sand silt	120-135	12-8
GC	clayey gravels, poorly graded gravel-sand-clay	115-130	14-9
SW	well-graded clean sands, gravelly sand	110-130	16-9
SP	poorly graded clean sand, sand-gravel mix	100-120	21-12
SM	silty sands, poorly graded sand-silt mix	110-125	16-11
SM-SC	san-silt-clay mix with slightly plastic fines	110-130	15-11
SC	clayey sands, poorly graded sand-clay mix	105-125	19-11
ML	inorganic silts and clayey silts	95-120	24-12
ML-CL	the mixture of organic silt and clay	100-120	22-12
CL	inorganic clays of low-to-medium plasticity	95-120	24-12
OL	organic silts and silt-clays, low plasticity	80-100	33-21
MH	inorganic clayey silts, elastic silts	70-95	40-24
CH	inorganic clays of high plasticity	75-103	36-19
OH	organic and silty clays	65-100	45-21

Table 3.3. The Angle of Internal Friction of Sandy Soils (Lindeburg, 1986)

			the angle of internal friction ∅	
type of soil	SPT, N	relative density D_r	Peck et al, 1974	Meyerhof, 1956
very loose sand	<4	<0.02	<29	<30
loose sand	4-10	0.2-0.4	29-30	30-35
medium sand	10-30	0.4-0.6	30-36	35-40
dense sand	30-50	0.6-0.8	36-41	40-45
very dense sand	>50	>0.8	>41	>45

Table 3.4. Cohesion and Friction Angles of Soils (Lindeburg, 1986)

group symbol	cohesion (as compacted), c (kPa)	cohesion (saturated) c_{sat} (kPa)	effective stress friction angle ∅
GW	0	0	>38
GP	0	0	>37

GM	-	-	>34
GC	-	-	>31
SW	0	0	38
SP	0	0	37
SM	50	20	34
SM-SC	50	14	33
SC	74	11	31
ML	67	9	32
ML-CL	65	22	32
CL	86	13	28
OL	-	-	-
MH	72	20	25
CH	100	11	19
OH	-	-	-

Some conversion formulas should be used to determine dry density, saturated density, water content, and degree of saturation. The specific gravity values required to be able to calculate using these formulas are taken from Table 3.5. To make these calculations, the void ratio was obtained from specific gravity by using the dry density formula given in the known Formula 1. Then, using known parameters, saturated density was calculated from Formula 2. Saturated water content was calculated using Formula 3, assuming that the soil reaches 100% saturation and the selected specific gravity value is a saturated soil value. Then, Poisson's ratio and modulus of elasticity were obtained from Table 3.6 and Table 3.7, respectively. Finally, the permeability values were determined based on the ranges given in Table 3.8.

Table 3.5. Specific Gravity of Soil (USBR, 1990)

				compaction				
		specific gravity		**laboratory**		**index density**		
USCS soil type	**total no. of samples tested**	**no. 4 minus**	**no. 4 plus**	**max. dry density kg/m^3**	**optimum moisture content**	**max. kg/m^3**	**min kg/m^3**	**values listed**
GW	22	2.69	2.58	1989	11.4	2167	1748	average
		0.03	0.08	51	1.2	139	128	std. dev.
		2.63	2.39	1907	9.9	1810	1417	minimum
		2.75	2.67	2042	13.3	2332	1896	maximum
		17	10	5		20		# of tests
SW	20	2.67	2.57	2019	9.1	1987	1576	average
		0.03	0.03	96	1.7	128	142	std. dev.
		2.64	2.54	1896	7.4	1683	1278	minimum

		2.72	2.59	2162	11.2	2207	1758	maximum
		13	2	4		13		# of tests
SC	112	2.69	2.47	1906	12.4			average
		0.04	0.18	99	2.4			std. dev.
		2.56	2.17	1547	6.7			minimum
		2.84	2.59	2109	22.1			maximum
		110	4	90				# of tests

$$\rho_d = \frac{(SG)p_w}{1+e} \tag{3.5}$$

$$\rho_{sat} = \frac{(SG+e)p_w}{1+e} \tag{3.6}$$

$$S = \frac{w(SG)}{e} \tag{3.7}$$

$\rho_d = dry\ density$

$p_{sat} = saturated\ density$

$\rho_w = density\ of\ water$

$e = void\ ratio$

$SG = specific\ gravity$

$S = saturation\ degree$

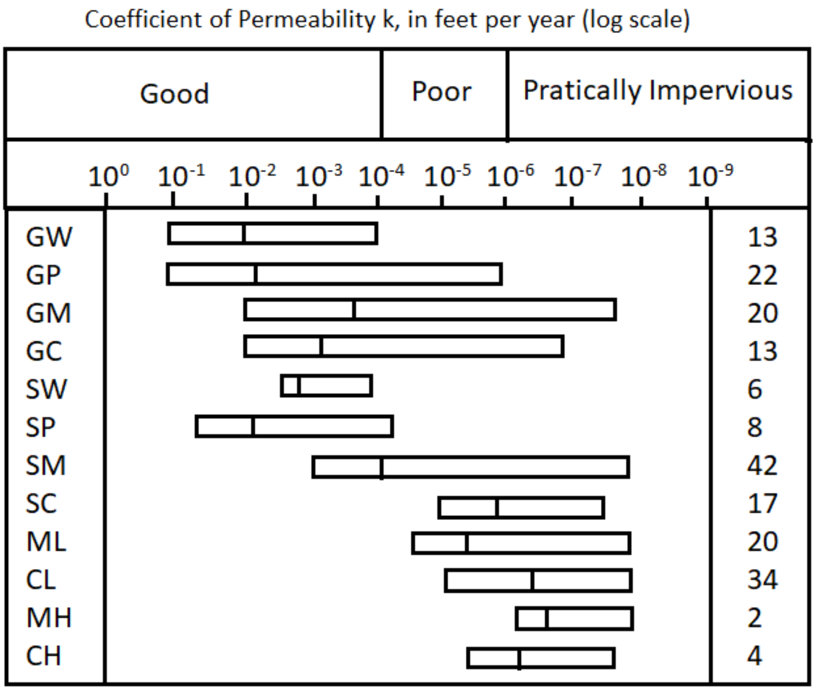
Table 3.6. Poission Ratio of Soils

type of soil	Poisson ratio μ
clay (saturated)	0.4-0.5
clay (unsaturated)	0.1-0.3
sandy clay	0.2-0.3
silt	0.3-0.35
sand (dense)	0.2-0.4
course (void ratio=0.4-0.7)	0.15
fine-grained (void ratio=0.4-0.7)	0.25
rock	0.1-0.4 (depends on the type of rock)
loess	0.1-0.3
ice	0.36
concrete	0.15

Table 3.7. Modulus Elasticity of Soils

type of soil	modulus of elasticity $(E_{ref,})(N/mm^2)$
clay	
very soft	2-15
soft	5-25
medium	15-50
hard	50-100
sandy	25-250
glacial till	
loose	10-153
dense	144-720
very dense	478-1140
loess	14-57
sand	
silty	7-21
loose	10-24
dense	48-81
sand and gravel	
loose	48-148
dense	96-192
shale	144-14400
silt	2-20

Table 3.8. The Permeability Properties of Soils (USBR, 1990)



Based on a combination of these parameters derived from experiments and observations from different sources, putative soil properties were determined for clayey gravel (GC), clayey sand (SC), and sand (SW). In designing dams, it is not possible to use these soil characteristics to capture the true nature of the soil. Because the purpose of this study is to determine the effect of changing the filter structure and properties on seepage, rather than designing a real dam, it is necessary to ignore the variations in soil parameters resulting from different conditions.

Data collected in Table 3.9 provide the final state of soil parameters for use in the design of this dam. The determination of soil properties, which is the first step in the design of a dam, has been completed. In the later sections of this thesis, stability and seepage analyses will be conducted based on these data. It is now necessary to make the physical design of the main dam.

Table 3.9. Final Properties of Soils

Parameters	**Embankment**		**Core**		**Filter**	
Soil	GC	Clayey Gravel	SC	Clayey Sand	SW	Sand
Unsaturated Unit Weight kN/m^3	18,064-20,427	19,2455	16,495-19,633	18,064	17,279-20,427	18,853
Saturated Unit Weight kN/m^3		21,667		20,843		21,469
Permeability m/s	$10^{-4} - 10^{-9}$	10^{-5}	$10^{-7} - 10^{-10}$	10^{-8}	$10^{-2} - 10^{-4}$	10^{-2}
Modulus of Elasticity kN/m^2	96000-192000	144000	25000-250000	137500	48000-81000	64500
Poisson Ratio	0,15	0,15	0,2-0,3	0,25	0,15	0,15
Cohesion kN/m^2	0	0	74-11	42,5	0	0
Angle of Friction	>31	37	31	31	30-36	33
Optimum Water Content	14-9	0,115	19-11	0,15	16-9	0,125
Specific Gravity	2,73-2,50	2,615	2,69-2,47	2,58	2,67-2,57	2,62
Void Ratio (from Formula)		0,328		0,396		0,363
Saturated Water Content (from Formula)		0,125		0,153		0,138

3.2.2 Dam Section Design

The first step in determining the section of the dam is to determine the height of the dam. In this study, since the effect of the water head in the reservoir on seepage will be investigated, the height of the dam was determined according to the reservoir water head. It was noted that dams with a height of more than 50 meters are classified as large dams by ICOLD when classifying them according to their height. Since the maximum reservoir height determined in this study was 100 m, the dam height was determined above this value. The crest height of the dam must be the sum of the maximum water head plus the freeboard height plus the flood control pool plus 3% of the dam's height (USACE, 2004). The height of this dam was determined as 103 meters. The crest width of the dam does not have much effect on the stability of the embankment dam and is designed according to the purpose it will serve. The recommended range for the crest width determined according to the height of the dam is between 7.6 m and 12.2 (USACE, 2004). The crest width of this dam was determined as 10 m.

The main factor affecting the stability of the dam is the angle of the upstream and downstream parts of the dam with the horizontal plane, that is, the slope of the dam. It is recommended that slopes for homogeneous dams constructed from fine-grained soils be between 3H:1V and 4H:1V for upstream slopes and 2.5H:1V for downstream slopes according to USBR (USBR, 1987). By considering factors such as the internal friction angle of the material used in this study as well as the drainage lengths needed to design the dam, the slope of the dam was determined to be 2.52H:1V. The homogeneous dam section determined according to these design principles is shown in Figure 3.3.

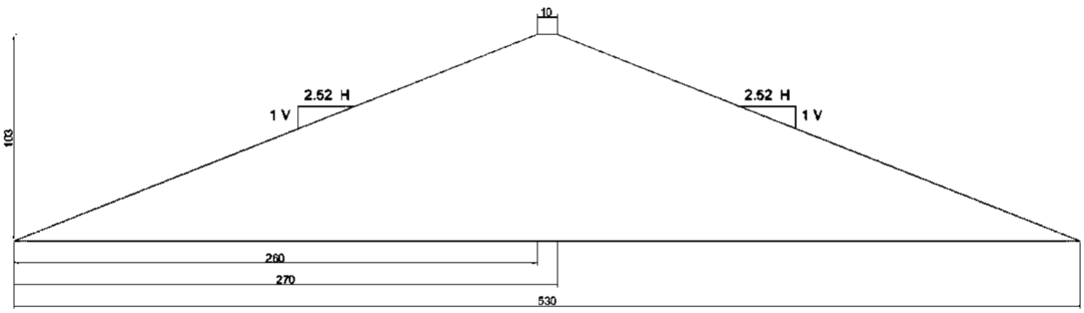


Figure 3.3. The Final Dimensions of the Dam

In the phase of determining the cross-section of the dam, the standard design dimensions in the manuals, the design criteria to meet the needs of the dams to be analyzed in SEEP/W, and the limits of the soil properties were taken into consideration. A stability analysis of the section was conducted after the section was determined and an evaluation was conducted to determine whether the dam design was appropriate. As a result of the fact that homogeneous and undrained embankment dams are the weakest type of dam against infiltration conditions, which was assessed at this stage, the dam was selected as homogeneous and without a filter. In the next step, resistance to collapse and other geotechnical properties of this homogeneous dam will be examined with Plaxis 2D software.

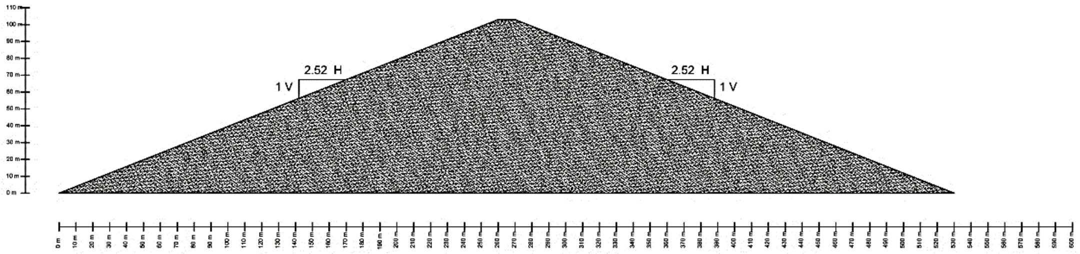


Figure 3.4. The Final Section of the Dam

3.2.3 Stability Analysis with Plaxis 2D

The Plaxis 2D CE V20 version was used for the stability analysis of the dam. The first step in analyzing Plaxis begins with the section drawing. Following the definition of the dam section in the software, the material properties are entered. Unit weight of soil, permeability coefficients, modulus of elasticity, void ratio, cohesion parameter, and friction angles are defined in the software at this stage. Since the foundation was considered to be completely impermeable, the foundation was not included in the program. Instead, an attempt was made to understand how the dam would act. After defining the ground parameters, the water head in the reservoir is defined. Since the maximum reservoir water head for this dam was determined as 100 meters, the analysis was made according to the water head.

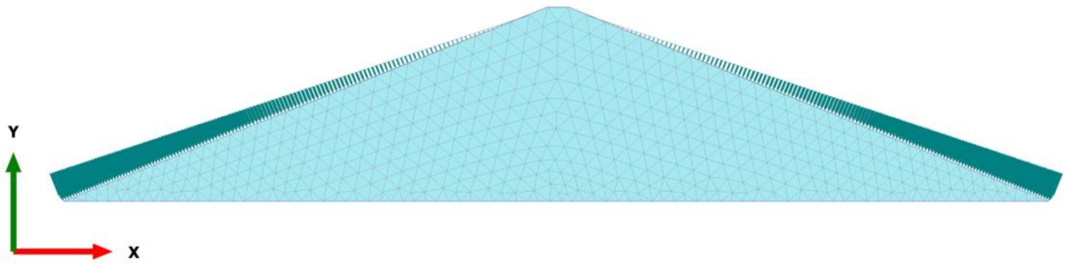


Figure 3.5. Dam Body After Meshed in Plaxis 2D

In the results of the analysis made in Plaxis 2D software, it was first investigated whether the dam collapsed. The design of the dam has made it resistant to collapse. There has been a total settlement of 0.4486 meters in the dam body. The areas where this settlement is intense are visualized in Figure 3.6 from red to dark blue. It was decided that this settlement, calculated for maximum water head, is safe. Shortly, the soil conditions and dam section selected for the dam are appropriate for its design.

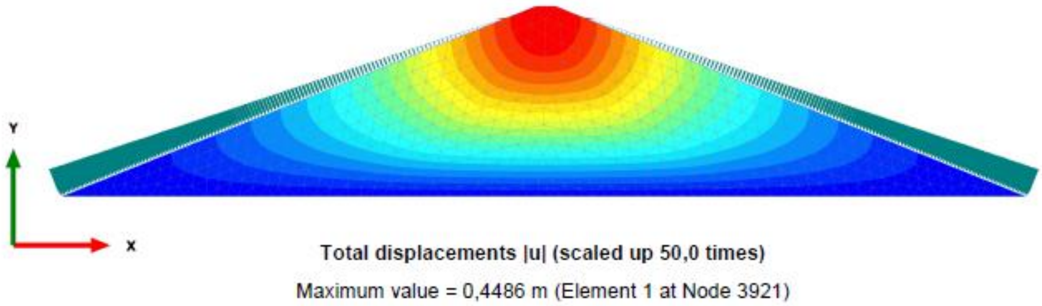


Figure 3.6. Total displacements at dam body

3.3 Dam Design with a Filter

Having verified the dam's durability and ensured its reliability for maximum water heads, the next step was to determine the parameters to be adhered to in the drainage design, as well as their magnitudes. It is necessary to provide some background information before discussing these variables. Design codes have been determined for each dam designed so that it is possible to reach all the features of the analyzed dam with its code. For blanket filter systems, the abbreviation "B" will be preceded by the three-digit threshold code, "C" for the chimney filter, and "T" for the toe filter. The dam type is divided into two: homogeneous embankment dams and zoned embankment dams. Soil permeability has always been considered impermeable. In the first instance, a blanket filter was used for drainage. Variables for this filter:

- The water head in the reservoir
- The thickness of the blanket filter
- Permeability of the soil used in the filter
- Length of blanket

This study analyzed 81 dams for dams with a blanket filter and selected 50m, 75m, and 100m levels of reservoir water in each dam. Because it is known that the seepage changes with the height of the water. Other variables are as follows: the thickness of the horizontal filter is 50 cm, 100 cm, and 200 cm, and the permeability of the filter $10^{-2}, 10^{-3}, and\ 10^{-4}$, and the length of the filter is 100 m, 150 m, and 200 m. Dams designed with the above elements are summarized in Table 3.10 along with their characteristics.

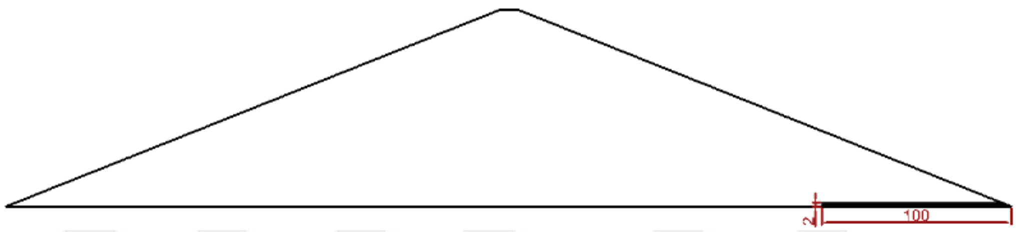


Figure 3.7. A dam with 2 m thickness and 100 m length blanket filter

Table 3.10. Properties of Dams with Blanket Filter

Code	Type of Dam	Length of Drainage m	Permeability of Drainage m/s	The thickness of the Drainage cm	The water head of the Reservoir m
B101	Homogeneous	100	10^{-2}	50	50
B102	Homogeneous	100	10^{-2}	50	75
B103	Homogeneous	100	10^{-2}	50	100
B104	Homogeneous	100	10^{-2}	100	50
B105	Homogeneous	100	10^{-2}	100	75
B106	Homogeneous	100	10^{-2}	100	100
B107	Homogeneous	100	10^{-2}	200	50
B108	Homogeneous	100	10^{-2}	200	75
B109	Homogeneous	100	10^{-2}	200	100
B110	Homogeneous	100	10^{-3}	50	50
B111	Homogeneous	100	10^{-3}	50	75
B112	Homogeneous	100	10^{-3}	50	100
B113	Homogeneous	100	10^{-3}	100	50

B114	Homogeneous	100	10^{-3}	100	75
B115	Homogeneous	100	10^{-3}	100	100
B116	Homogeneous	100	10^{-3}	200	50
B117	Homogeneous	100	10^{-3}	200	75
B118	Homogeneous	100	10^{-3}	200	100
B119	Homogeneous	100	10^{-4}	50	50
B120	Homogeneous	100	10^{-4}	50	75
B121	Homogeneous	100	10^{-4}	50	100
B122	Homogeneous	100	10^{-4}	100	50
B123	Homogeneous	100	10^{-4}	100	75
B124	Homogeneous	100	10^{-4}	100	100
B125	Homogeneous	100	10^{-4}	200	50
B126	Homogeneous	100	10^{-4}	200	75
B127	Homogeneous	100	10^{-4}	200	100
B128	Homogeneous	150	10^{-2}	50	50
B129	Homogeneous	150	10^{-2}	50	75
B130	Homogeneous	150	10^{-2}	50	100
B131	Homogeneous	150	10^{-2}	100	50
B132	Homogeneous	150	10^{-2}	100	75
B133	Homogeneous	150	10^{-2}	100	100
B134	Homogeneous	150	10^{-2}	200	50
B135	Homogeneous	150	10^{-2}	200	75
B136	Homogeneous	150	10^{-2}	200	100
B137	Homogeneous	150	10^{-3}	50	50
B138	Homogeneous	150	10^{-3}	50	75
B139	Homogeneous	150	10^{-3}	50	100
B140	Homogeneous	150	10^{-3}	100	50
B141	Homogeneous	150	10^{-3}	100	75
B142	Homogeneous	150	10^{-3}	100	100
B143	Homogeneous	150	10^{-3}	200	50
B144	Homogeneous	150	10^{-3}	200	75
B145	Homogeneous	150	10^{-3}	200	100
B146	Homogeneous	150	10^{-4}	50	50
B147	Homogeneous	150	10^{-4}	50	75
B148	Homogeneous	150	10^{-4}	50	100
B149	Homogeneous	150	10^{-4}	100	50
B150	Homogeneous	150	10^{-4}	100	75
B151	Homogeneous	150	10^{-4}	100	100
B152	Homogeneous	150	10^{-4}	200	50
B153	Homogeneous	150	10^{-4}	200	75
B154	Homogeneous	150	10^{-4}	200	100
B155	Homogeneous	200	10^{-2}	50	50
B156	Homogeneous	200	10^{-2}	50	75
B157	Homogeneous	200	10^{-2}	50	100
B158	Homogeneous	200	10^{-2}	100	50
B159	Homogeneous	200	10^{-2}	100	75

B160	Homogeneous	200	10^{-2}	100	100
B161	Homogeneous	200	10^{-2}	200	50
B162	Homogeneous	200	10^{-2}	200	75
B163	Homogeneous	200	10^{-2}	200	100
B164	Homogeneous	200	10^{-3}	50	50
B165	Homogeneous	200	10^{-3}	50	75
B166	Homogeneous	200	10^{-3}	50	100
B167	Homogeneous	200	10^{-3}	100	50
B168	Homogeneous	200	10^{-3}	100	75
B169	Homogeneous	200	10^{-3}	100	100
B170	Homogeneous	200	10^{-3}	200	50
B171	Homogeneous	200	10^{-3}	200	75
B172	Homogeneous	200	10^{-3}	200	100
B173	Homogeneous	200	10^{-4}	50	50
B174	Homogeneous	200	10^{-4}	50	75
B175	Homogeneous	200	10^{-4}	50	100
B176	Homogeneous	200	10^{-4}	100	50
B177	Homogeneous	200	10^{-4}	100	75
B178	Homogeneous	200	10^{-4}	100	100
B179	Homogeneous	200	10^{-4}	200	50
B180	Homogeneous	200	10^{-4}	200	75
B181	Homogeneous	200	10^{-4}	200	100

Another type of filter used in this study is the toe filter, and some variables have been determined for this filter:

- The water head in the reservoir
- The slope of the toe filter
- Permeability of the soil used in the filter
- Length of the filter

81 varied dam designs consisting of these variables were determined and seepage analysis was performed. The reservoir water head was again determined as 50 m, 75 m, and 100 m, and the angle of the heel filter with the horizontal ground was determined as 30°, 60°, and 90°. The permeability was determined in three different types as $10^{-2}, 10^{-3}, and\ 10^{-4}$, the length of the heel filter was chosen as 50m, 100m, and 150m.

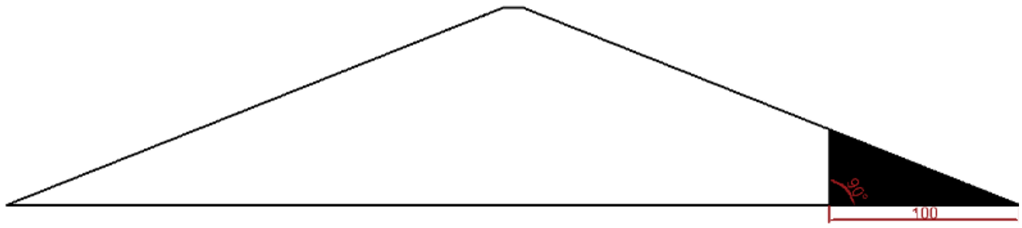


Figure 3.8. A dam with 100 m length and 90° toe filter

Table 3.11. Properties of Dams with Toe Filter

Code	Type of Dam	Length of Drainage m	Slope of Drainage °	Permeability of Drainage m/s	The water head of the Reservoir m
T101	Homogenous	50	30	10^{-2}	50
T102	Homogenous	50	30	10^{-2}	75
T103	Homogenous	50	30	10^{-2}	100
T104	Homogenous	50	30	10^{-3}	50
T105	Homogenous	50	30	10^{-3}	75
T106	Homogenous	50	30	10^{-3}	100
T107	Homogenous	50	30	10^{-4}	50
T108	Homogenous	50	30	10^{-4}	75
T109	Homogenous	50	30	10^{-4}	100
T110	Homogenous	50	60	10^{-2}	50
T111	Homogenous	50	60	10^{-2}	75
T112	Homogenous	50	60	10^{-2}	100
T113	Homogenous	50	60	10^{-3}	50
T114	Homogenous	50	60	10^{-3}	75
T115	Homogenous	50	60	10^{-3}	100
T116	Homogenous	50	60	10^{-4}	50
T117	Homogenous	50	60	10^{-4}	75
T118	Homogenous	50	60	10^{-4}	100
T119	Homogenous	50	90	10^{-2}	50
T120	Homogenous	50	90	10^{-2}	75
T121	Homogenous	50	90	10^{-2}	100
T122	Homogenous	50	90	10^{-3}	50
T123	Homogenous	50	90	10^{-3}	75
T124	Homogenous	50	90	10^{-3}	100
T125	Homogenous	50	90	10^{-4}	50
T126	Homogenous	50	90	10^{-4}	75
T127	Homogenous	50	90	10^{-4}	100
T128	Homogenous	100	30	10^{-2}	50
T129	Homogenous	100	30	10^{-2}	75
T130	Homogenous	100	30	10^{-2}	100
T131	Homogenous	100	30	10^{-3}	50
T132	Homogenous	100	30	10^{-3}	75

T133	Homogenous	100	30	10^{-3}	100
T134	Homogenous	100	30	10^{-4}	50
T135	Homogenous	100	30	10^{-4}	75
T136	Homogenous	100	30	10^{-4}	100
T137	Homogenous	100	60	10^{-2}	50
T138	Homogenous	100	60	10^{-2}	75
T139	Homogenous	100	60	10^{-2}	100
T140	Homogenous	100	60	10^{-3}	50
T141	Homogenous	100	60	10^{-3}	75
T142	Homogenous	100	60	10^{-3}	100
T143	Homogenous	100	60	10^{-4}	50
T144	Homogenous	100	60	10^{-4}	75
T145	Homogenous	100	60	10^{-4}	100
T146	Homogenous	100	90	10^{-2}	50
T147	Homogenous	100	90	10^{-2}	75
T148	Homogenous	100	90	10^{-2}	100
T149	Homogenous	100	90	10^{-3}	50
T150	Homogenous	100	90	10^{-3}	75
T151	Homogenous	100	90	10^{-3}	100
T152	Homogenous	100	90	10^{-4}	50
T153	Homogenous	100	90	10^{-4}	75
T154	Homogenous	100	90	10^{-4}	100
T155	Homogenous	150	30	10^{-2}	50
T156	Homogenous	150	30	10^{-2}	75
T157	Homogenous	150	30	10^{-2}	100
T158	Homogenous	150	30	10^{-3}	50
T159	Homogenous	150	30	10^{-3}	75
T160	Homogenous	150	30	10^{-3}	100
T161	Homogenous	150	30	10^{-4}	50
T162	Homogenous	150	30	10^{-4}	75
T163	Homogenous	150	30	10^{-4}	100
T164	Homogenous	150	60	10^{-2}	50
T165	Homogenous	150	60	10^{-2}	75
T166	Homogenous	150	60	10^{-2}	100
T167	Homogenous	150	60	10^{-3}	50
T168	Homogenous	150	60	10^{-3}	75
T169	Homogenous	150	60	10^{-3}	100
T170	Homogenous	150	60	10^{-4}	50
T171	Homogenous	150	60	10^{-4}	75
T172	Homogenous	150	60	10^{-4}	100
T173	Homogenous	150	90	10^{-2}	50
T174	Homogenous	150	90	10^{-2}	75
T175	Homogenous	150	90	10^{-2}	100
T176	Homogenous	150	90	10^{-3}	50
T177	Homogenous	150	90	10^{-3}	75
T178	Homogenous	150	90	10^{-3}	100

T179	Homogenous	150	90	10^{-4}	50
T180	Homogenous	150	90	10^{-4}	75
T181	Homogenous	150	90	10^{-4}	100

Lastly, the chimney filter will be examined in the study. When compared to the other types of filters, the chimney filter is preferred more in zoned dams rather than homogeneous ones. Therefore, dams designed with chimney filters are preferred as clay core dams. While designing the clay core, a 40 m base width and 10 m top width were preferred. Variable parameters in this filter type, which is designed to cover the downstream part of the clay core:

- The water head in the reservoir
- The thickness of the chimney filter
- Permeability of the soil used in the filter
- Height of chimney filter.

Again, depending on these variables, 81 dams were determined and the reservoir water head and the permeability of the ground were kept the same as the variables in other dams. In this case, the variables that differ are the chimney thickness, which is determined as 50 cm, 100 cm, and 200 cm, and the height of the top of the filter from the foundation, which is determined as 50 m, 100 m, and 200 m.

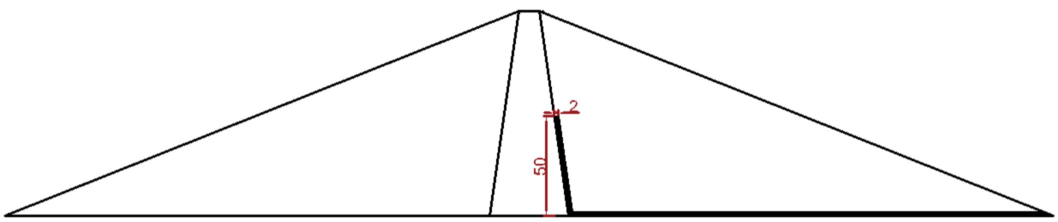


Figure 3.9. A dam with 2 m thickness and 50 m height chimney filter

Table 3.12. Properties of Dams with Chimney Filter

Code	Type of Dam	Height of Drainage m	Permeability of Drainage m/s	The thickness of the Drainage cm	The water head of the Reservoir m
C101	Zoned	50	10^{-2}	50	50
C102	Zoned	50	10^{-2}	50	75
C103	Zoned	50	10^{-2}	50	100
C104	Zoned	50	10^{-2}	100	50
C105	Zoned	50	10^{-2}	100	75

C106	Zoned	50	10^{-2}	100	100
C107	Zoned	50	10^{-2}	200	50
C108	Zoned	50	10^{-2}	200	75
C109	Zoned	50	10^{-2}	200	100
C110	Zoned	50	10^{-3}	50	50
C111	Zoned	50	10^{-3}	50	75
C112	Zoned	50	10^{-3}	50	100
C113	Zoned	50	10^{-3}	100	50
C114	Zoned	50	10^{-3}	100	75
C115	Zoned	50	10^{-3}	100	100
C116	Zoned	50	10^{-3}	200	50
C117	Zoned	50	10^{-3}	200	75
C118	Zoned	50	10^{-3}	200	100
C119	Zoned	50	10^{-4}	50	50
C120	Zoned	50	10^{-4}	50	75
C121	Zoned	50	10^{-4}	50	100
C122	Zoned	50	10^{-4}	100	50
C123	Zoned	50	10^{-4}	100	75
C124	Zoned	50	10^{-4}	100	100
C125	Zoned	50	10^{-4}	200	50
C126	Zoned	50	10^{-4}	200	75
C127	Zoned	50	10^{-4}	200	100
C128	Zoned	75	10^{-2}	50	50
C129	Zoned	75	10^{-2}	50	75
C130	Zoned	75	10^{-2}	50	100
C131	Zoned	75	10^{-2}	100	50
C132	Zoned	75	10^{-2}	100	75
C133	Zoned	75	10^{-2}	100	100
C134	Zoned	75	10^{-2}	200	50
C135	Zoned	75	10^{-2}	200	75
C136	Zoned	75	10^{-2}	200	100
C137	Zoned	75	10^{-3}	50	50
C138	Zoned	75	10^{-3}	50	75
C139	Zoned	75	10^{-3}	50	100
C140	Zoned	75	10^{-3}	100	50
C141	Zoned	75	10^{-3}	100	75
C142	Zoned	75	10^{-3}	100	100
C143	Zoned	75	10^{-3}	200	50
C144	Zoned	75	10^{-3}	200	75
C145	Zoned	75	10^{-3}	200	100
C146	Zoned	75	10^{-4}	50	50
C147	Zoned	75	10^{-4}	50	75
C148	Zoned	75	10^{-4}	50	100
C149	Zoned	75	10^{-4}	100	50
C150	Zoned	75	10^{-4}	100	75
C151	Zoned	75	10^{-4}	100	100

C152	Zoned	75	10^{-4}	200	50
C153	Zoned	75	10^{-4}	200	75
C154	Zoned	75	10^{-4}	200	100
C155	Zoned	100	10^{-2}	50	50
C156	Zoned	100	10^{-2}	50	75
C157	Zoned	100	10^{-2}	50	100
C158	Zoned	100	10^{-2}	100	50
C159	Zoned	100	10^{-2}	100	75
C160	Zoned	100	10^{-2}	100	100
C161	Zoned	100	10^{-2}	200	50
C162	Zoned	100	10^{-2}	200	75
C163	Zoned	100	10^{-2}	200	100
C164	Zoned	100	10^{-3}	50	50
C165	Zoned	100	10^{-3}	50	75
C166	Zoned	100	10^{-3}	50	100
C167	Zoned	100	10^{-3}	100	50
C168	Zoned	100	10^{-3}	100	75
C169	Zoned	100	10^{-3}	100	100
C170	Zoned	100	10^{-3}	200	50
C171	Zoned	100	10^{-3}	200	75
C172	Zoned	100	10^{-3}	200	100
C173	Zoned	100	10^{-4}	50	50
C174	Zoned	100	10^{-4}	50	75
C175	Zoned	100	10^{-4}	50	100
C176	Zoned	100	10^{-4}	100	50
C177	Zoned	100	10^{-4}	100	75
C178	Zoned	100	10^{-4}	100	100
C179	Zoned	100	10^{-4}	200	50
C180	Zoned	100	10^{-4}	200	75
C181	Zoned	100	10^{-4}	200	100

3.4 Seepage Analysis with SEEP/W

For the analyses to be made in this study, SEEP/W software of GeoStudio 2018 R2 version was preferred. A dam modelling in SEEP/W is a rather simple process. After dam properties and dam section are clarified, there are four basic steps to analyze the dam in SEEP/W:

- First Step = Determine the shape of the dam.
- Second Step = Determine the material properties of the dam.
- Third Step = Determine boundary conditions.
- Fourth Step = Solve the problem and analyze the results.

The first step to be performed for seepage analysis, as similar software does, is to process the dam section as geometry properties into the software There is an important point to must be mentioned, in SEEP/W software if the foundation is determined impermeable, it is not necessary to draw a foundation to determine the discharge of the seepage in the dam body. The next step is to define material properties. SEEP/W seepage analysis requires the soil saturation state to be taken into account when defining the material for the analysis. In this study, analyses were made for both saturated and unsaturated state conditions. It is important to define two parameters at this stage: volumetric water content and hydraulic conductivity. There is an estimation function provided by the software for volumetric water content calculation. Based on the type of material and the saturation water content of the saturated material, the software calculates volumetric water content as a logarithmic function. This stage involves the definition of the hydraulic conductivity function using the saturated permeability value and residual water content parameters as a Van Genuchten function. After defining the material properties, the boundary conditions must be defined. As part of this process, the filter and the water head in the reservoir are identified. Afterwards, mesh properties must be defined. All dams were analyzed with a mesh size of 2 m in this study. Then, seepage analysis was performed.

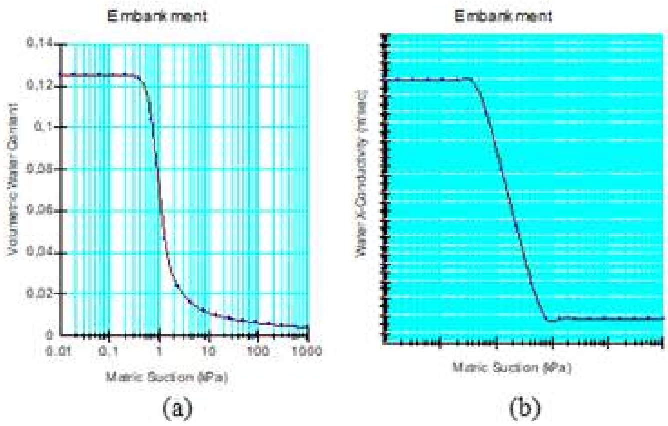


Figure 3.10. Parameter Functions of Embankment Soil in SEEP/W (a) Volumetric Water Content Function (b) Hydraulic Conductivity Function

Sections were determined in the dam body so that the results of the seepage analysis could be evaluated and compared with each other. The sections were determined at 100-meter intervals beginning at the point where the upstream part of the dam intersects with the ground, as shown in Figure 3.10. According to the upstream dam toe, Section 1, Section 2, Section 3, Section 4, and Section 5 are located 100 m, 200 m, 300 m, 400 m, and 500 m ahead respectively. Using these sections, the results of the analysis will be interpreted and 273 dams will be studied in order to understand seepage movement and the seepage in their bodies.

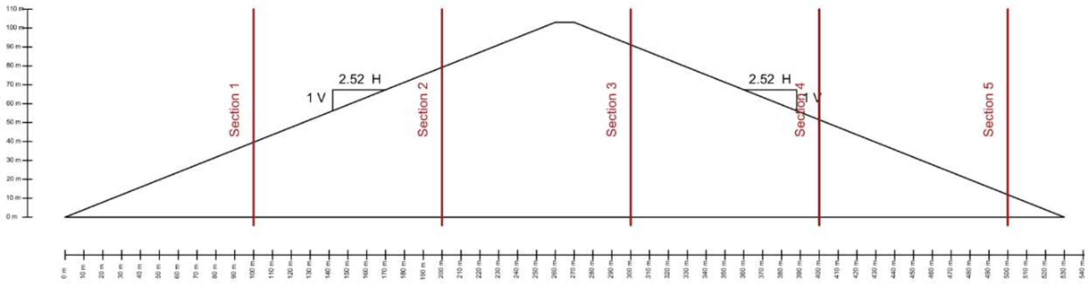


Figure 3.11. Sections to be examined in the dam body

CHAPTER 4
ANALYSIS AND DISCUSSION

In this part of the study, the data obtained as a result of the modelling of 273 embankment dams will be examined in terms of seepage and maximum water head in the sections for five different sections. In the first stage, the results will be divided into three main headings according to the filter type used in the dams: blanket, toe, and chimney. Following that, each filter type will be examined in terms of the variable accepted feature. For example among blanket filters, there are triple dam groups with different blanket thicknesses, while all other features are the same. To put it another way, seepage analysis was conducted for three different blanket thicknesses of 27 dam groups with varying properties. The similarity or difference between the increases and decreases in these three groups will allow us to make inferences about the effect of blanket thickness on seepage. By analyzing these steps over other variables and other filter groups, it will be possible to understand which parameter is effective for seepage in filter design. In addition, different filter types will be compared with each other and it will be understood which is the most ideal design and which filters cause unsuccessful results.

4.1 Blanket Filter

This section examines the SEEP/W modelling of 81 embankment dams, whose design features were discussed earlier with the B1XX code, as well as the analysis of the seepage and water head in five different sections. It attempted to understand the effect of the design variables of the filter systems on seepage by analyzing 81 varied dam designs. To understand the effect of a single variable on seepage, three dam groups were formed in this study to understand the behavior of four key variables (water head, filter thickness, permeability of soil, and blanket length). For example, while the reservoir water head in the B101, B102, and B103 dams is different, all other variables of this dam are the same. In other words, they have the same blanket thickness and length with the same filter permeability. If this method is applied to the remaining dams, the effect of 3 different reservoir water heads can be observed on 27 varied dam designs. To analyze the effect of the variable whose effect is being researched, graphs will be drawn for the triple dam groups of the data collected from the sections, and 27 varied dam designs will be compared to the variable whose effect is to be understood.

4.1.1 The Effect of the Water Head

In embankment dams, it is known that the head of the reservoir water is effective on seepage in the dam, in line with the information obtained from previous studies. One of the factors emphasized in this study is the effect of the water head in the dam on seepage. It was preferred to examine this on graph for Section 1, Section 2, Section 3, Section 4, and Section 5 rather than the seepage in the overall dam body and maximum seepage in the section being determined.

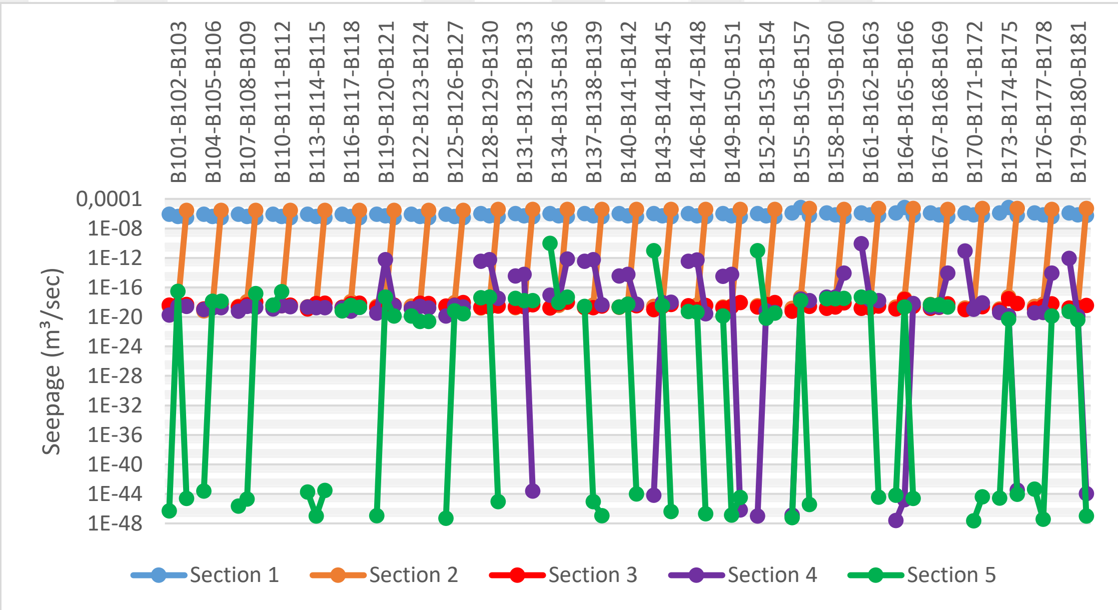


Figure 4.1. Maximum Seepage in Sections for the Change in the Water Head

As can be seen from Figure 4.1 below, the horizontal axis displays the names of the dam triples examined. On the vertical axis, it gives information about the maximum seepage rate in that section. According to the analysis of the seepage behavior of dams B101, B102, and B103, which are respectively designed for 50 m, 75 m, and 100 m reservoir water heads, the maximum seepage discharge in Section 1 decreases as the reservoir head increases. This behavior was analyzed to be similar in all dams except B155-B156-B157, B164-B165-B166, and B173-B174-B175. These dam triples exhibit the same blanket thickness and length but differ in filter permeability. In the transition from 50 m to 75 m water head, the maximum seepage for Section 1 is steeply reduced, but for the transition from 75 m to 100 m water head, the decrease is more limited. In Section 2, it is observed that the seepage behavior has changed. A decrease in maximum seepage was observed for 50 m and 75 m water heads, with closely matched values, whereas a huge increase was observed for 100 m water heads.

Based on Figure 4.1 it is not possible to see a parallel seepage behavior for 27 varied dam designs as in other sections. While the increase in water head in the reservoir caused an increase in the amount of some in some dams for Section 3, a decrease was observed in the seepage flow in some dams after 75 m of water head. It would not be appropriate to make a deduction on the reasons for the changes since they are not linear and each dam group is designed with different characteristics.

On the maximum seepage of Section 4, it can also be observed that the change in the reservoir water head also results in different seepage rates for different dams. It has been observed that the head of reservoir water is not a factor in determining the maximum seepage discharge in some dams, while in others, such as B131-B132-B133, it has been observed that the maximum seepage decreases when the water head is increased from 75 m to 100 m. It is also possible to analyze the dam groups in which the opposite situation is seen in the graph. In the same manner, the uneven distribution in Section 5 complicates the interpretation of a linear change in reservoir level. Despite the similarity of the seepage behaviors of dam groups in Sections 1 and 2, seepage behavior differs at different reservoir levels for various dams from Section 3.

It is possible to see in the graph that the reservoir water head has a definite effect on the seepage in the dam body. The only factor that changes in these dam groups, which are designed with the same characteristics, is the water head in the dam reservoir. However, it can be seen that the effect of this change is not linear. In other words, the reservoir water head has a significant effect on seepage behavior in a homogeneous dam body designed with a blanket filter. However, when it comes to analyzing the effect of this change on the maximum seepage in the dam body, it should be studied separately for each dam.

As part of analyzing the reservoir level’s effect on the seepage behavior in different sections of the dam, another point that should be considered is its effect on the water head in the sections. Taking into account the water head in the sections allows us to better understand the path followed by the phreatic line. According to the graph generated by the analyses conducted in this section, Figure 4.2 shows that, as expected, a rise in the reservoir level results in a rise in the water head in the dam body, regardless of the design of the dam. It should be noted in Section 1, Section 2, and Section 3 that the rate of increase between 50 m and 75 m and then 100 m reservoir water head is also similar.

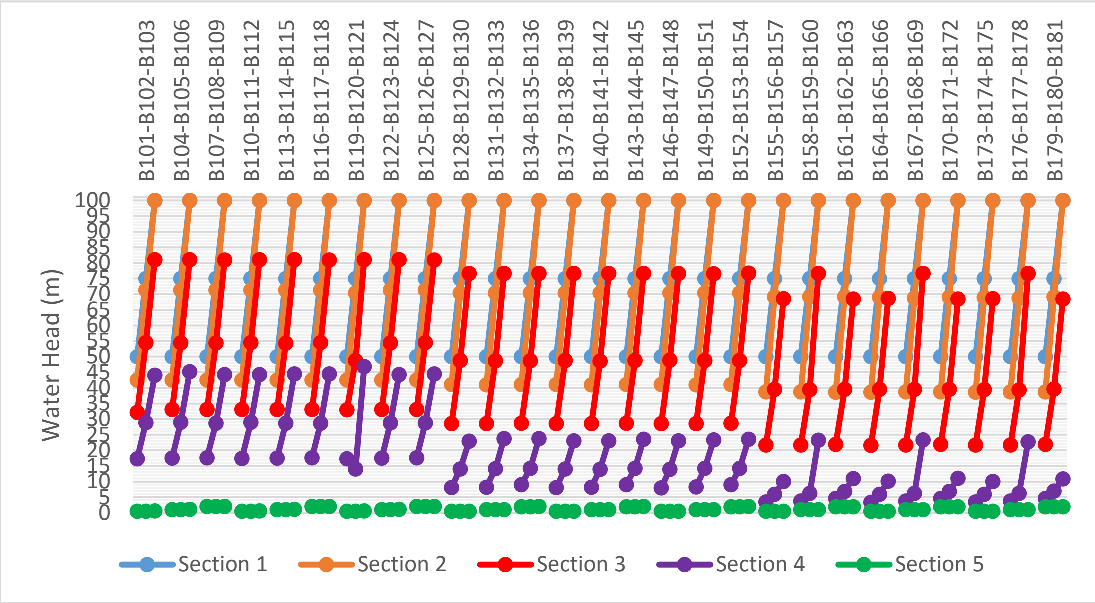


Figure 4.2. Water Head in Sections for the Change in the Water Head

Similarly, Section 4 shows that when the reservoir level increases, the water head in the dam body also rises. The only difference is that in B158-B159-B160 and several dams, there is a high increase in the rise from the 75 m reservoir level to 100 m. Detailed characteristic analyses are necessary for gaining a better understanding of the reasons for this difference. In this study, the integrity of the subject will not be distributed by entering these details. This is evident in the graph of Section 5, where the phreatic line, which rises as reservoir levels increase in the dam body, reaches similar levels downstream. Based on the graph, it can be concluded that there has been only a slight increase or stability in the water head in this section for the reservoir levels of 50 m, 75 m, and 100 m.

To summarize, it has been tried to understand the effect of the change in the reservoir water head on seepage in 27 dams with blanket filters of different thicknesses, lengths, and permeability. When the reservoir level is raised, the maximum seepage in Sections

1 and 2 increases. It is not possible to make similar inferences for the remaining sections because the results showed different behavior for dam groups with different filter properties. As the water head increased, the water head in the sections increased as well for Section 1, Section 2, and Section 3. Different dam groups experienced different rates of increase in Section 4. However, when Section 5 was examined, no significant differences were observed in section water heads. As a result, it was seen that the change in the dam reservoir affects seepage behavior for a homogeneous blanket-filtered embankment dam.

4.1.2 The Effect of the Permeability of Filter Material

Among the other parameters to be examined is the permeability of the filter material, which will affect the seepage of blanket filter dams. The classification of dams is carried out to understand the impact that permeability changes have on both the seepage in the dam sections as well as the water head within the sections as a result of changes in 10^{-2},10^{-3}, and 10^{-4} ratios. There are triple dam groups in this chapter, like in other chapters, with the same characteristics, but the permeability is different. The analysis steps followed in the previous chapter will also be followed in this part of the study.

If the graph is examined, it can be seen that the seepage values of the dam groups grouped in three such as B101-B110-B119 are respectively expressed in the graph. The results are represented, with the triple point group where the permeability decreases gradually, with the first point representing the highest permeability threshold. Once again, it should be noted that this method is being applied to 27 varied dam designs and they will not be compared because the effect of permeability is being explored. In this context, examining the graph in Figure 4.3, it can be seen that the decrease in the permeability of the filter material by 1/10 does not have a significant impact on the maximum seepages for Sections 1, 2, and 3. A closer look at the graph reveals that this small change does not cause a regular increase or decrease. The decrease in permeability for different dam groups caused different effects on the maximum seepage behavior in these sections. A decrease in permeability was associated with a reduction in seepage in some cases, but an increase in seepage was observed in others.

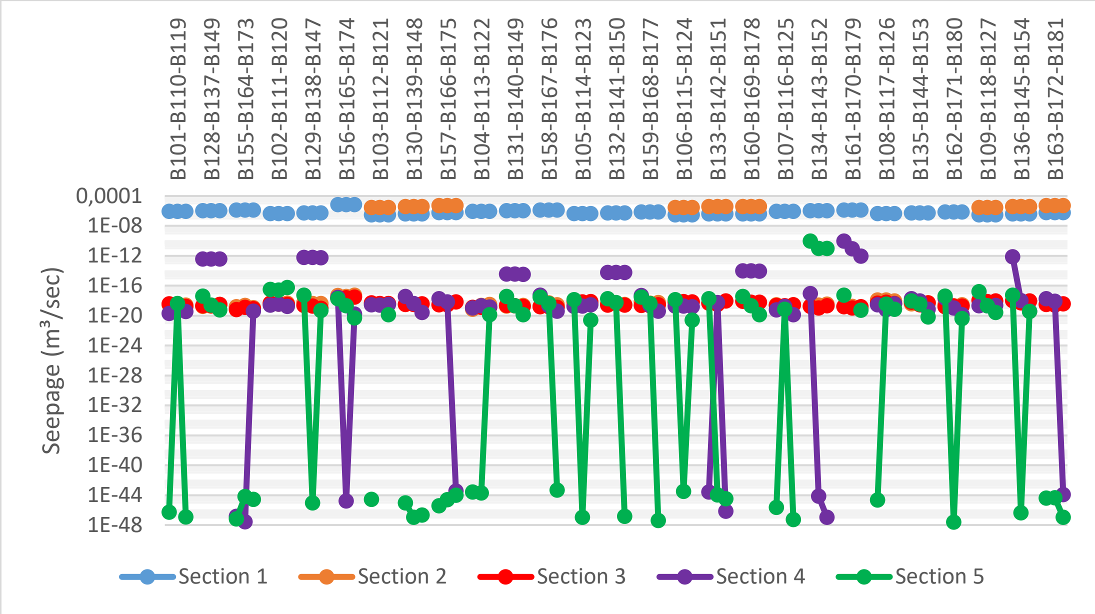


Figure 4.3. Maximum Seepage in Sections for the Change in the Permeability of Filter Material

In Section 4, the seepage graph presents a sharper trend as the permeability changes than in the first three sections of the dams, showing a minimal change in maximum seepages. Several dam groups within Section 4 had significantly reduced seepage rates due to decreased permeability, including B157-B166-B175, B134-B143-B152, and B163-B172-B181. In contrast, in the B155-B167-B173 and B156-B165-B174 dam groups, the seepage increased as permeability transitioned from 10^{-3} to 10^{-4}. Looking at the graph for Section 5, it is seen that there is much more variable seepage behavior than in Section 4. While the change in permeability has a minimal effect on some varied dam designs, it is seen that it causes more serious seepage rate differences in other dam designs. It is not possible to define these changes as a single behavior in terms of increase and decrease. Because the dams did not exhibit regular behavior in the regular decrease of permeability.

Overall, studies examining 27 varied dam designs with different filter permeabilities were conducted for blanket-filtered embankment dams, indicating that while the dams did not cause significant changes in the first three sections, they caused very different seepage behaviors near the blanket filters in the dam regions. Since it is not possible to reach a general opinion about these behaviors, the effect of permeability on the seepage should be analyzed by making a dam-based study.

The effect of dam permeability, which is another point to be examined, on the maximum water head in the dam section can be interpreted by examining the graph given in Figure 4.4. Based on the results, it is apparent that the change in permeability does not cause serious changes in the water head in any of the dam's sections. The behavior of very small increases or decreases does not follow a linear pattern for all varied designs of dams. The only exception is seen in the change in seepage permeability from the 10^{-3} level to the 10^{-4} level in the B103-B112-B121 dam group. The water head in the section rises by approximately 2.5 m for the B121 dam. Considering the situation in this one dam requires an examination of the dam itself, therefore it will not be discussed in this report.

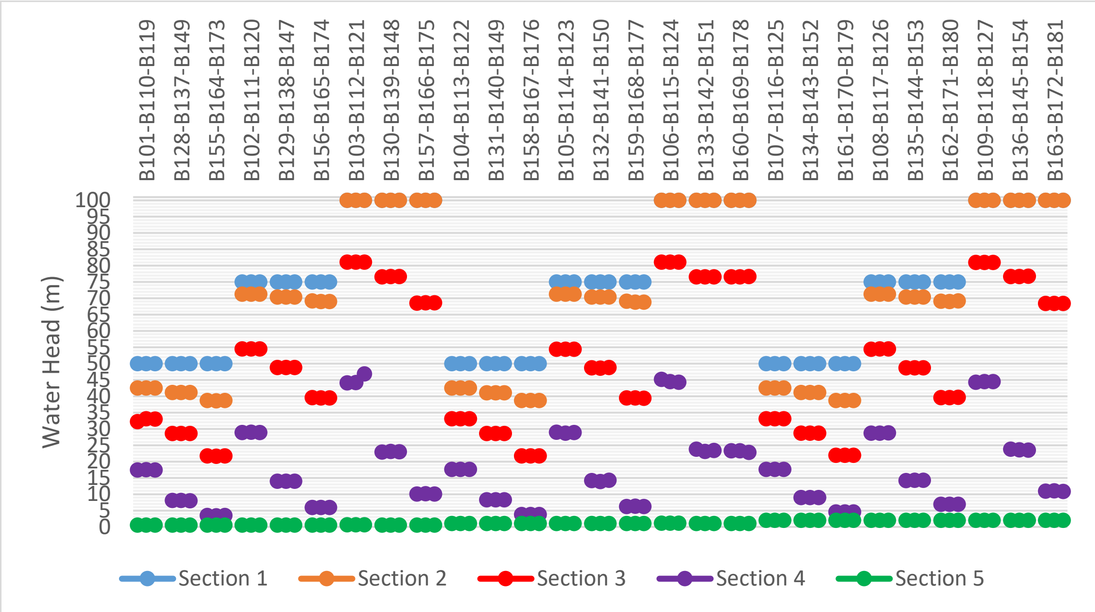


Figure 4.4. Water Head in Sections for the Change in the Permeability of Filter Material

The research conducted on the dam with 27 different blanket filters revealed, as a result of the findings, that the decreased permeability of the filter material did not significantly affect the seepage in the first three sections of the dam, but rather affected the behavior of seepage in the section containing the filter material. This change does not show a linear increase or decrease. The effect on the water head in all sections of the dam was negligible.

4.1.3 The Effect of Blanket Length

It will be examined in this section how the blanket filter length affects the seepage behavior of the dam body. A blanket filter design was made to have a length of 100 m, 150 m, and 200 m, respectively, from the downstream heel of the dam. Analysis results of 27 varied dam designs consisting of triple dam groups with equal permeability, reservoir water head, and blanket thickness are graphed. In dams in the same group, as the dam code increased, the blanket length increased, respectively.

In the graph for Section 1, the increase in blanket length in almost all dams increased the seepage in the section. It can be seen in the graph that the seepage increases rapidly with the transition from 150 meters to 200 meters for B102-B129-B156, B111-B138-B165, and B120-B147-B174. This regular behavior in Section 1 begins to change in Section 2. In this section, as the blanket length increases, there are dams such as B126-B153-B180 that show a regular decrease in the seepage, and on the contrary, B108-B135-B162 where there is a regular increase in the seepage. It is also possible to observe dams that do not show a linear increase or decrease in this way.

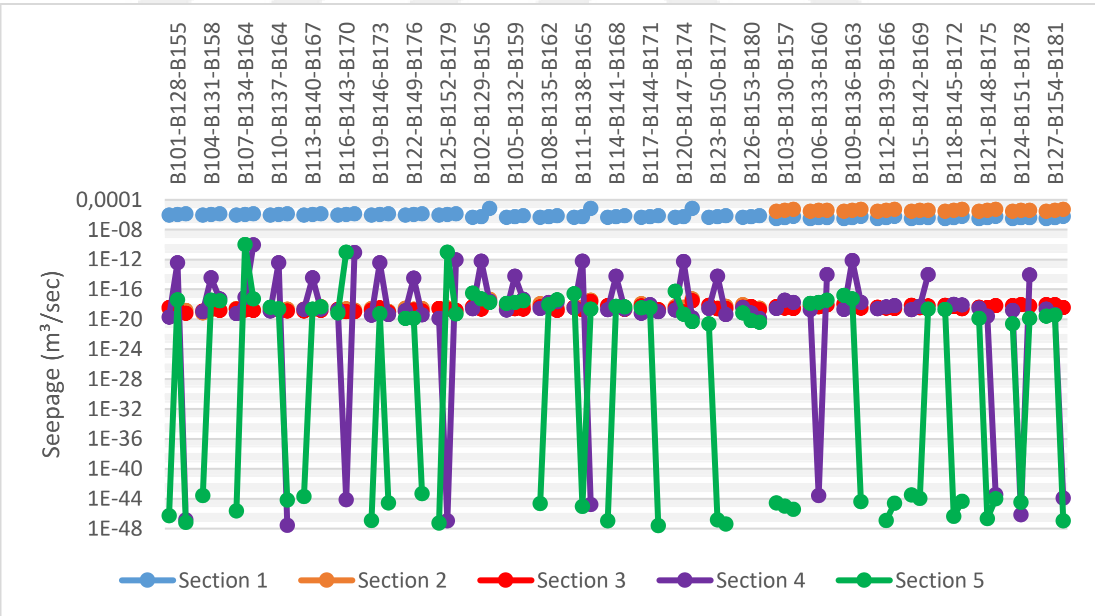


Figure 4.5. Maximum Seepage in Sections for the Change in the Blanket Length

The plot of Section 3 is similar to the plot of Section 2. Since the maximum seepage values in this section are in the same range for 27 varied dam designs, it is possible to establish a more detailed comparison of the change in seepage between varied dam designs. By looking at the graph, it can be interpreted that the maximum seepage in the section does not show a regular increase or decrease as the blanket length increases. The amounts of these increases and decreases are not linear in dams such as B102-B129-B156. Based on the graph of this variation design of the dam, it appears that seepage decreases as blanket length increases from 100 m to 150 m, but increases at a different rate from 150 m to 200 m. On the graph for Section 4 and Section 5, it can be noted that the attitudes of the dam groups are highly variable, and the seepage in those sections is highly dependent on the design properties of the dam. Some dams in the given section experienced a significant increase or decrease in seepage in response to the longer blanket, but the length of the blanket did not cause serious changes in varied dam designs B103-B130-B157.

As a conclusion drawn from all graphs, blanket length has an impact on maximum seepage in dam sections. However, the variability of this effect is observed with more serious differences in the sections where the blanket filter is located. It should be noted that this behavior is not linear. In other words, it is not possible to say that the seepage in the section will increase or decrease as the blanket length increases. It is important to examine each dam independently.

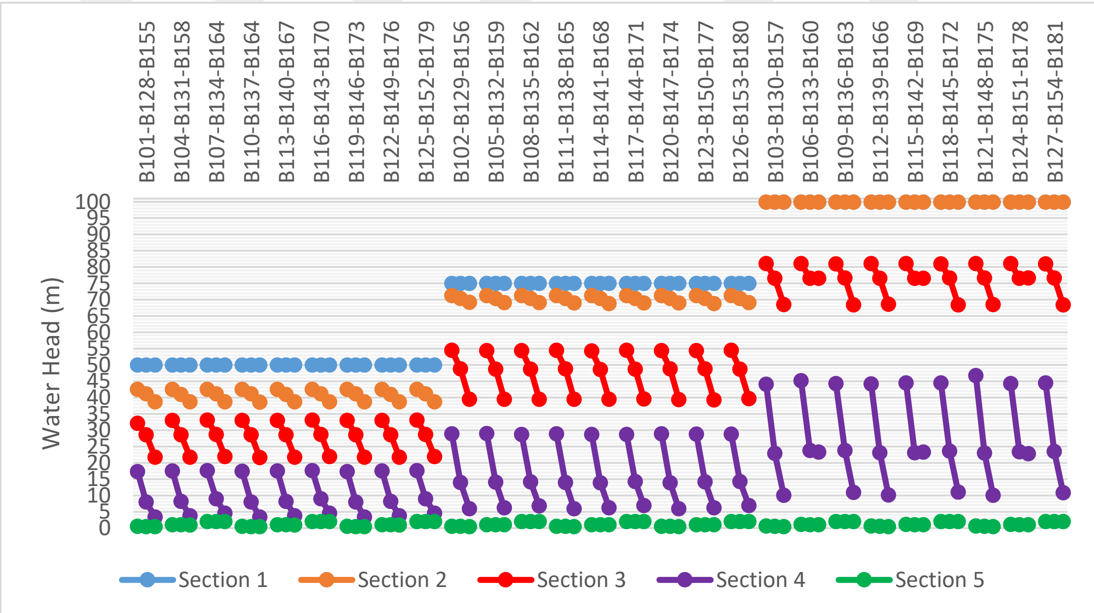


Figure 4.6. Water Head in Sections for the Change in the Blanket Length

According to the cross-section water head graph, which is the other point we examined while analyzing seepage behavior in the same sections, the water head in Section 1 is unaffected by blanket length. In Section 2, the water head decreases with increasing blanket length. It is more noticeable at dams with a reservoir head of 50 m, but less noticeable at 75 m and 100 m reservoir heads. In the graph for Section 3, the effect of blanket length increase on the decrease in water head in the section can be seen more clearly. In this instance, it is important to note that while the blanket length is extended from 100 m to 150 m, the decrease in cross-sectional water head is smaller than the decrease from 150 m to 200 m. Exceptionally, increases in blanket length from 150 m to 200 m have no significant impact on water head changes in Section 3 and Section 4 for varied dam designs B106-B133-B160, B115-B142-B169, and B124-B151-B178. The graph for Section 4 more clearly shows the effect of blanket length on the water head in the dam section. The blanket length increase from 100 m to 150 m leads to a substantial decrease in water head, and the increase of blanket length from 150 m to 200 m follows this decrease, but less so. The decrease in the water head in the cross-section seen with increased blanket length occurs at a minimal level in Section 5. According to this perspective, the water head in the areas closest to the upstream part of the dam is not affected by an increase in blanket length, but it decreases significantly towards the center of the dam if the blanket length is increased. And there is a slight decrease in the downstream region.

4.1.4 The Effect of the Blanket Thickness

The blanket filter's thickness is another parameter studied for its effect on seepage. Three types of filters with 50 cm, 100 cm, and 200 cm thicknesses were used in this study. For 27 varied dam designs, the thickness of the filter was increased in three-fold groups, and five different sections of the dam were studied for use in determining how seepage is affected. Maximum seepage discharge and maximum water head were determined for all these sections. Based on these analyses, it will be possible to determine whether blanket thickness variation exhibits a general behavior of seepage across varied dam designs and sections.

The increase in filter thickness for the first section of the dam did not have a serious effect on the seepage in the section. It has been observed that a decrease in the seepage has been observed in the dam groups B156-B159-B162, B165-B168-B171, and B174-B177-B180 at the transition from 50 cm to 100 cm in thickness, but this decrease did not persist at 100 cm to 200 cm in thickness. Many varied designs of dams experienced increased seepage with an increase in filter thickness in Section 2. However, it is not possible to make inferences about the direction of a linear increase and decrease as different dams show different responses. To see this volatility more clearly, Section 3 can be examined. Section 4 is an example of a clear illustration of the effect of blanket thickness on the maximum seepage. In this section, the increase in blanket thickness in varied dam designs such as B137-B140-B143 and B146-B149-B152 significantly reduced the seepage in the section. On the contrary, there are dams such as B155-B158-B161 and B164-B167-B170 which cause a very serious increase in the seepage in the section. These different behaviors can be attributed to varied dam designs. There has been evidence that the thickness increase in varied dam designs such as B103-B106-B109 and B112-B115-B118 does not result in serious volatility in the seepage under these conditions.

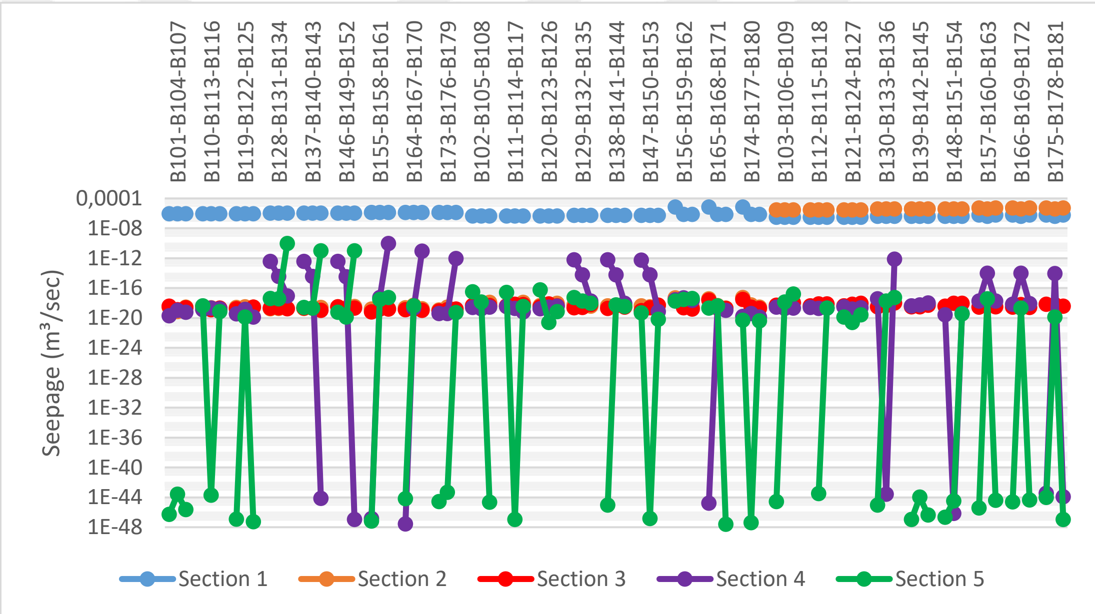


Figure 4.7. Maximum Seepage Sections for the Change in the Blanket Thickness

In Section 5, the impact of the thickness of the blanket on the seepage is highly noticeable. In this section, serious changes are seen in the seepage with the increase in filter thickness in varied dam designs. There are varied designs of dams in which a significant increase and decrease are observed simultaneously as the thickness increases, instead of the more typical increase and decrease. Addressing the reasons for this means examining the dams one by one and including other factors that distract from the subject of this study. For this reason, it would be healthier to continue with general inferences. The increase in the thickness of the blanket certainly affects the seepage in different sections of the dam body. It is not possible to say that this effect follows a clear behavior within the scope of the data obtained. In other words, for a homogeneous and blanket-filtered dam, the effect of increasing or decreasing the thickness on seepage should be determined by the study of the dam in question.

Another situation to be examined is the effect of increasing the filter thickness on the water head in the sections. If the graphics of the first three sections in Figure 4.8 are examined, it is seen that the increase in blanket thickness in these sections does not have a serious effect on the water head in these sections. But as can be seen in Section 3, the water head increases as the thickness increases from 50 cm to 100 cm for the varied dam designs B157-B160-B163, B166-B169-B172, and B175-B178-B181. For the same dams, the water head in the section decreases as the blanket thickness increases from 100 cm to 200 cm.

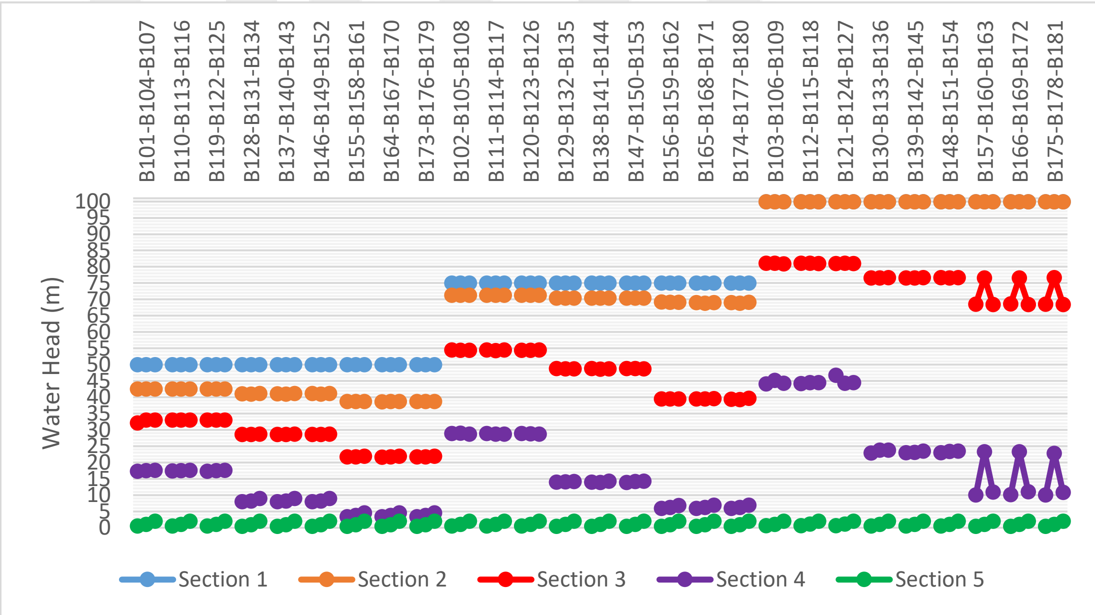


Figure 4.8. Water Head for Sections for the Change in the Blanket Thickness

As a result of the increase in blanket filter thickness for Section 4, there was a change in the water head, which was not the case in other sections. In some dam designs, as the section thickness increased, the water head decreased, while in others it first increased and then decreased. It is not possible to define a regular behavior pattern for this section. In Section 5, as the section thickness increased in all varied dam designs, the water head in the section increased and reached levels close to the blanket thickness.

To summarize, increasing the thickness of the blanket filter affects the seepage in a dam. While this effect causes smaller amounts of seepage to increase and decrease in the sections close to the upstream part of the dam, it causes sharper fluctuations in the downstream areas of the blanket. It has been shown through the analysis of 27 varied dam designs that there does not appear to be a definite pattern of behavior, and each dam must be studied separately. Likewise, the increase in filter thickness caused fluctuations in the maximum water head in the sections. These fluctuations are higher in the parts where the filter is located. Again, it is not possible to talk about a constant increase or decrease.

4.1.5 Phreatic Lines of Dams with Blanket Filter

The phreatic line is a significant factor in a dam's hydraulic behavior. It marks the boundary between the saturated and unsaturated zones within the dam's foundation and body. Engineers and hydrologists monitor the phreatic line to ensure the dam's safety and stability. Proper management of the phreatic line mitigates risks associated with water-related issues and maintains the long-term stability and functionality of dams. In this part of the study, the aim was to examine the phreatic line change in dams to determine the variables affecting optimum dam design.

The graph data presented shows that among dams with a reservoir water head of 50 m, the embankment dam coded B173 exhibits exceptional performance owing to its 50 cm blanket thickness, 200 m blanket length, and permeability coefficient of 10^{-4}. Interestingly, other dams that show comparable excellence, such as B155, B158, B163, B167, B176, and B179, also share an extended blanket length. This observation suggests that an increased blanket length has a positive impact on the overall performance of the dam structure.

On the other hand, the dam coded B125 exhibits suboptimal performance in terms of the phreatic line among dams with a 50 m water head due to its shorter blanket length of 100 m and a blanket thickness of 200 cm. Similarly, dams such as B104, B107, B110, B113, B116, B119, and B122 exhibit suboptimal performance due to their shorter blanket length. This finding provides further evidence that an increased blanket length positively affects dam efficiency.

For dams with a reservoir water head of 75 m, the graph highlights the superiority of the dam coded B174, which exhibits optimal performance with its design comprising a 50 cm blanket thickness, 200 m blanket length, and permeability coefficient of 10^{-4}. Similarly, other dams, including B156, B159, B165, B168, and B177, exhibit comparable excellence, emphasizing the positive impact of an extended blanket length on dam performance.

On the other hand, the dam coded B126 emerges as the underperformer in terms of the phreatic line among dams with a 75 m water head. Characterized by a shorter blanket length of 100 m and a blanket thickness of 200 cm, this dam aligns with others, including B102, B105, B108, B114, B117, and B123, in displaying suboptimal performance. These consistent findings reinforce the idea that an increased blanket length contributes positively to dam efficiency.

Moving on to embankment dams with a reservoir water head of 100 m, the spotlight shifts to the dam coded B175, which showcases optimal performance with a design comprising a 50 cm blanket thickness, 200 m blanket length, and permeability coefficient of 10^{-4}. Similarly, other dams such as B157, B163, B166, B172, and B181 also exhibit exceptional performance, sharing the common attribute of an extended blanket length.

However, the dam coded B121 emerges as the least efficient in terms of the phreatic line among dams with a 100 m water head, exhibiting suboptimal performance due to its shorter blanket length of 100 m and a blanket thickness of 50 cm. Other dams, including B103, B106, B109, B115, B118, B124, and B127, also exhibit suboptimal performance, reinforcing the correlation between increased blanket length and improved dam performance.

In summary, the results underscores the critical role of the phreatic line in dam hydraulic behavior, with a specific focus on dams at varying water head levels. The consistent trend observed indicates that an increased blanket length positively influences the phreatic line performance, as evidenced by the exemplary behavior of dams like B173, B174, and B175. These findings provide valuable insights for engineers, emphasizing the importance of optimizing blanket length in dam design to enhance stability and long-term functionality.

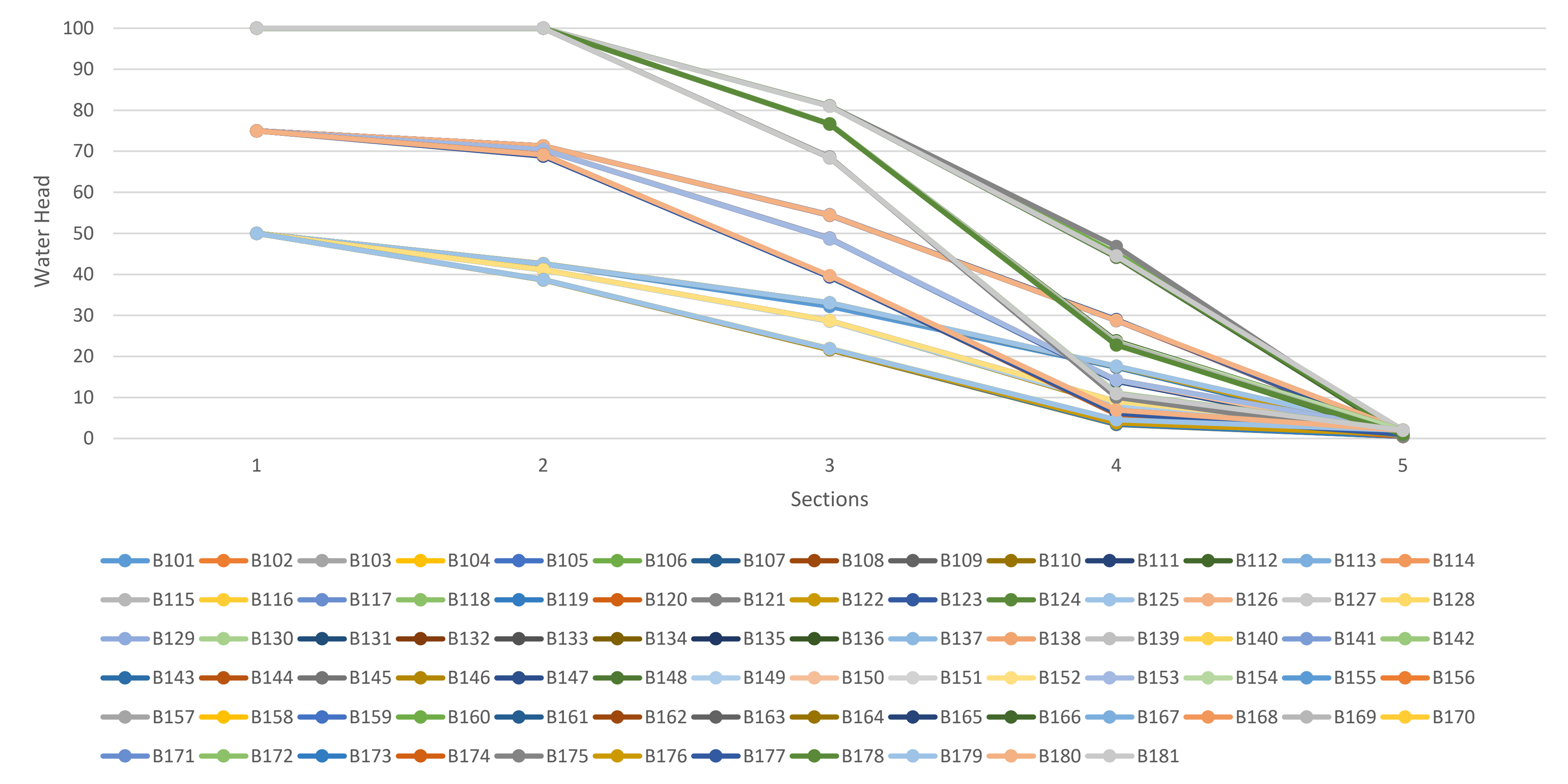


Figure 4.9. Phreatic Lines for Dams with Blanket Filter

4.2 Toe Filter

One of the types of filters studied in this study is the toe filter. The seepage behavior of a homogeneous embankment dam with a toe filter according to changing parameters has been tried to be analyzed by studies on 81 dams. These dams have received the T1XX code and seepage analysis has been done with SEEP/W. In the next stage, the analysis results were divided into 27 varied dam designs according to variables (the slope of the filter, its permeability, its length, and the water head of the reservoir). An evaluation of each dam was conducted for five different sections, in order to determine the seepage and water head in each section. Comparisons were made according to these parameters and the effect of the relevant variable on the dam was tried to be understood.

As a result of the effects of seepage on dam stability, 9 of the dams analyzed in this study failed. The variables that cause this result will be discussed in the relevant sections. This is the reason why data are not available for some dam groups or dams given in the charts.

4.2.1 The Effect of the Water Head

There were 27 varied dam designs analyzed according to three different reservoir water heads as previously stated. The analyzed reservoir water heads were determined as 50 m, 75 m, and 100 m. When these varied dam designs are divided into groups of three such as T101-T102-T103, it is seen that the water head in the reservoir increases as the value in the dam code increases. In other words, while the dam with code T101 has a reservoir water head of 50 m, the reservoir water head of the dam with code T103 is 100 m. At the same time, all the features of the T101, T102, and T103 dams are the same except for the water head. In other words, it is a dam group with the same filter permeability, the same toe slope, and the same filter base length, tested with different water heads. All these 27 dam groups have different features from each other and these features can be examined from the tables of dam codes and features given in the previous headings.

Another point to be reminded of is that the results of these analyses will be examined in 5 different sections of the dam body. A dam is divided into a series of sections, referred to as Section 1, Section 2, Section 3, Section 4, and Section 5. They are located at respective distances of 100 m, 200 m, 300 m, 400 m, and 500 m upstream of the dam base. In each section, first, the maximum seepage in the section will be examined, then the water head in these sections will be monitored and the effect of the water head in the dam reservoir on the seepage will be discussed.

If Section 1 is examined, for all homogeneous dams with toe filters, as the reservoir water head in the dam increases, the seepage in the section decreases. Looking at the groups where the two points are joined in the graph, it should be understood that one of the dams there failed. It should be noted that the reservoir water head in all failing dams is 100 m.

As can be seen from the plot of Section 2, the seepage behavior is different from the plot of Section 1. In this section, when the reservoir water head rises from 75 m to 100 m, the seepage increases significantly for all dams. It should be noted, however, that although the increase in the reservoir water head from 50 m to 75 m increases seepage, this increase is not as sharp and high a rate as that of the transition from 50 m to 100 m. Contrary to the intense change in te seepage in Section 2, it is seen that there are smaller changes in Section 3. From the graph, it is evident that increases or decreases seem to follow a similar pattern to Section 1. This part differs from the seepage behavior in Section 1 due to variable behavior. Observing a linear increase or decrease is not possible because dams behave differently.

Section 4 and Section 5 in the graph clearly show that the effect of reservoir water head on the seepage varies from dam to dam and even from section to section. Section 4 shows that the dam group T173-T174-T175 has a linear seepage increase with reservoir level and has the lowest seepage in the graph for Section 5 with a reservoir level of 75 m. While there is no significant increase or decrease in the seepage change in Section 4 of dam groups such as T119-T120-T121, the seepage decreased significantly when the reservoir level reached 75 m in Section 5. To summarize, it is seen that the reservoir water head has a serious effect on the seepage. However, when this effect is analyzed in terms of seepage in the sections of the dam body, it is seen that the dam needs to be examined specifically in order to understand the seepage behavior.

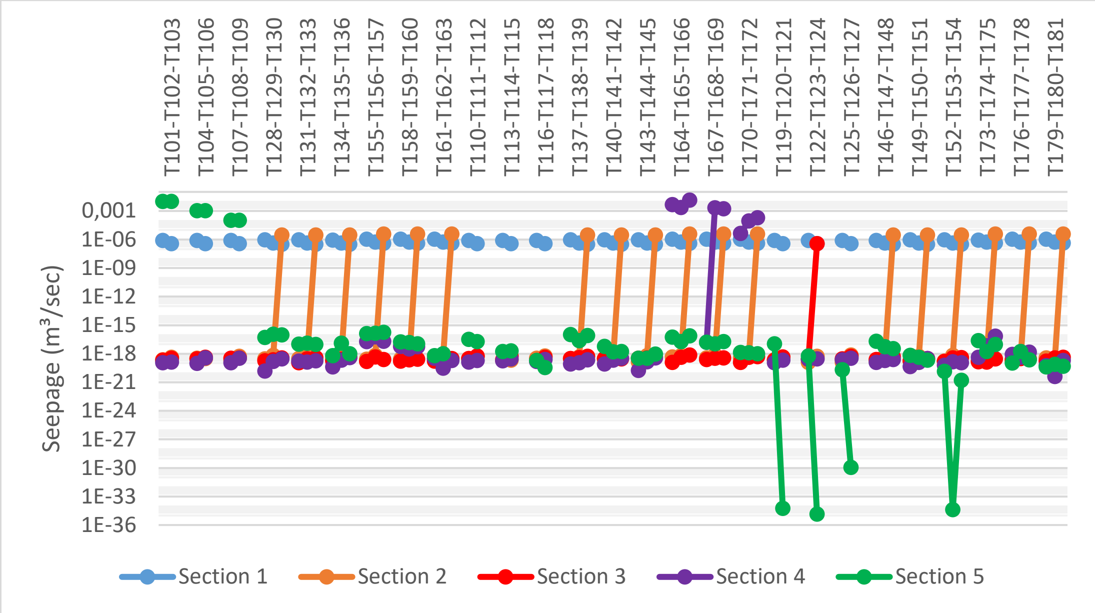


Figure 4.10. Maximum Seepage in Sections for the Change in the Water Head

After understanding the effect of the increase in the reservoir water head on the seepage in the specified sections of the dam in a homogeneous dam with a toe filter, its effect on the water head in these sections will be analyzed. Unless the dams are overtopped at 100 m water head (T103, T106, T109, etc.), the reservoir water head increases at the water head in these sections when examined by examining their Section 1, Section 2, and Section 3.

It is seen that the regular behavior exhibited in the first three sections changes in Section 4 of the dam. The increase in the reservoir level in the T173-T174-T175 dam group causes a decrease in the water head in the section. In the T176-T177-T178 and T179-T180-T181 dam design, the water head in the section first increased and then decreased. The reason for these behaviors can be determined by a detailed analysis of the dams. There is a noticeable difference in the behavior in Section 5 compared to other sections. Several dams in this section, including T128-T129-T130, are not affected by changes in the reservoir water head. A few dams show regular increases or decreases. Other dams, on the other hand, experience fluctuations in the water head rather than linear behavior. These show that different behaviors are exhibited in this section for different dams.

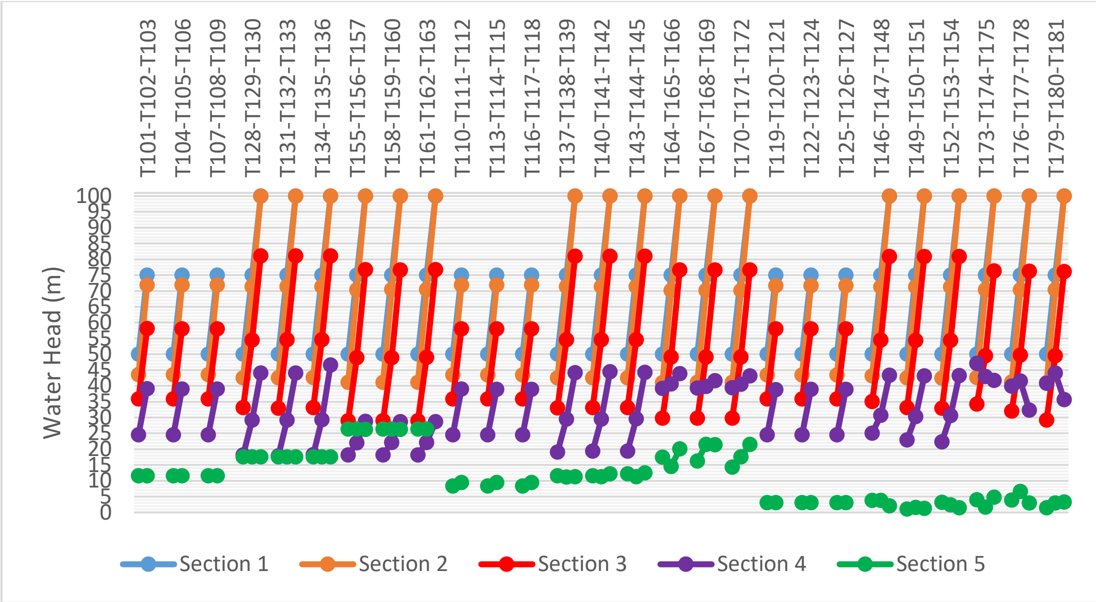


Figure 4.11. Water Head in Sections for the Change in the Water Head

In summary from all these graphs, it can be seen that the change in the water head affects the seepage. The magnitude or negligibility of this effect depends on the characteristics of the dam. Since this effect does not follow a regular pattern for some sections, it would be wrong to reach general conclusions. Analyzes should be made separately for the variation of dam design in question and its impact should be interpreted as such.

In addition, when the evaluations made within the scope of the toe filter and the behaviors made for the blanket filter are examined, it is seen that these graphs are quite different from each other. As the reservoir level increases in a toe filter dam, the change in the seepage in the sections is not as sharp as the changes seen in blanket filter dams. Likewise, the behavior of the water head in the dam sections is quite different.

4.2.2 The Effect of the Slope of the Filter

Another parameter that tries to understand the effect of a homogeneous dam with a toe filter on the seepage behavior in different sections is the slope of the toe filter. By performing the same steps as in the previous sections, that is, 27 varied dam designs were grouped in triplicate, and analyses were made for three different slope values. The 30°, 60°, and 90° angles here are the angles the toe filters make with the horizontal ground. In proportion to the increase in the number of dams grouped in threes such as T101-T110-T119, the angle upstream of the toe filter's vertical axis and the horizontal axis also increases. All analysis results were classified into five different sections and the maximum seepage and maximum water head in these sections were analyzed.

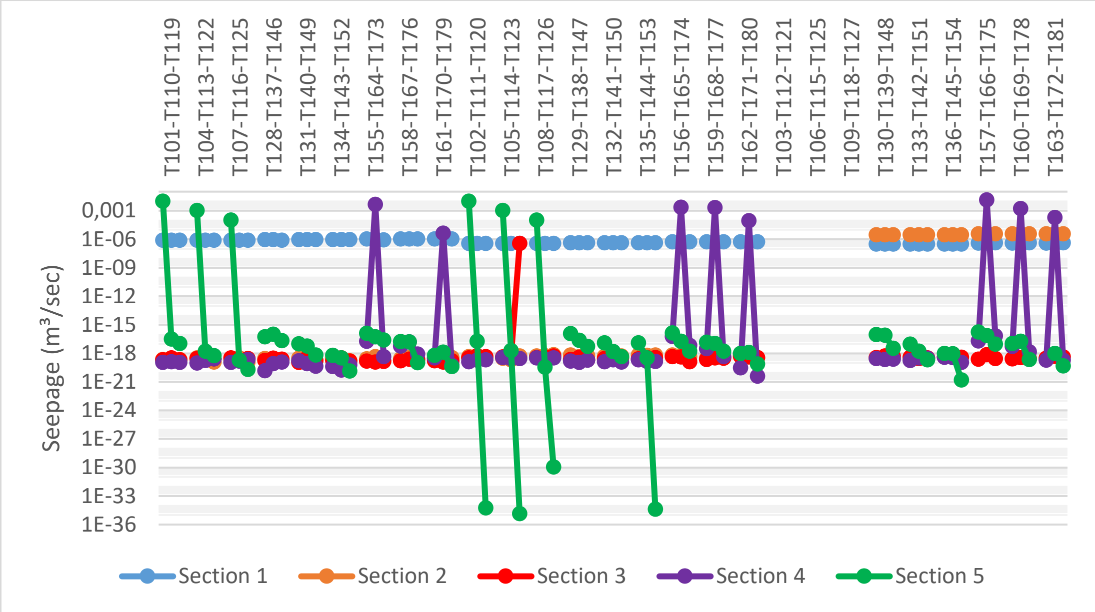


Figure 4.12. Maximum Seepage in Sections for the Change in the Slope of the Filter

It is seen that the increase in the angle of the filter with the horizontal does not cause serious changes in the seepage in Figure 4.11. For Section 1, there is almost no increase or decrease in dams except for a few variations of dam design. There are small increases and decreases in Section 2, but these increases and decreases do not occur in a certain order. In other words, although the angle of the dam with the horizontal increases regularly, seepage does not increase. There are dams where the seepage increases and then decreases, and there are dams where the opposite is true. This is the case for Section 3, except for the T105-T114-T123 dam group. In this group, when the angle increases from 60° to 90°, a very large increase in the seepage is observed. The reason for this is not within the scope of this study. Please be reminded once again that the dams whose names appear on the chart but whose data are empty fail.

Unlike the other sections, a different seepage behavior has developed in the graph for Section 4. As the angle of the toe filter with the horizontal ground increased from 30° to 60°, there was a very significant increase in seepage. However, when the angle was increased from 60° to 90°, the seepage fell dramatically and approached the seepage level of 30°. For Section 5, the seepage decreases as the angle of the filter increases. While this decrease in seepage occurred at a very serious rate in dams such as T102-

T111-T120, it was less in some dams such as T155-T164-T173. It can be interpreted that there is a general decrease in seepage behavior in this section, albeit in different amounts. The general inference is that changing the slope of the toe filter affects seepage. Although this effect is less pronounced and more variable upstream of the dam, in the downstream sections, where the toe filter resides, it produces more drastic changes in seepages.

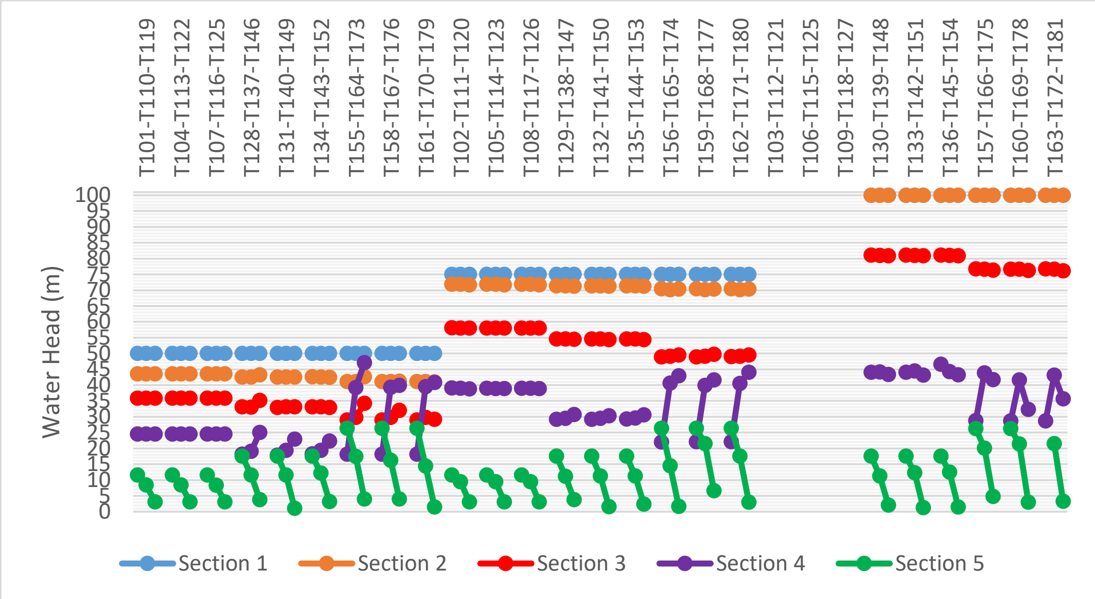


Figure 4.13. Water Head in Sections for the Change in the Slope of the Filter

The next step is to examine the effect of the change in the toe filter slope on the water head in the aforementioned sections. Figure 4.12 includes the graphs of all sections. When these graphs are examined, it is seen that the change in the angle of the filter with the horizontal for Section 1 and Section 2 does not affect the water head. For Section 3, it was determined that there was a significant increase in the water head in the section when the angle increased from 60° to 90° in a few dams such as T155-T164-T173. Minor increases or decreases were observed in other dams as well.

In Section 4, the change in the slope of the filter causes serious fluctuations in the water head. In almost half of the dams, except for those that fail, the head of the water increases as the degree made with the horizontal increases. While this increase is sharper in some dams when passing from 30° to 60°, in other dams it is much sharper in the transition from 60° to 90°. A linear increase is seen in a few dams. It has been observed that in some dams in which the water head does not increase, the water head remains constant, while in others it first rises and then decreases.

For Section 5, the increase in the angle of the toe filter with the horizontal ground in all dams reduces the water head in the section. Although the amount of this decrease varies from dam to dam, the water head in the downstream part is the lowest for dams with 90 toe filters for all dams.

To summarize, for a dam with a homogeneous toe filter, the change in the slope of the toe filter affects the seepage. While this effect causes more minimal changes in the first three sections of the dam, it causes more significant changes in the last sections of the dam. The reason for the high fluctuations here is that seepage is no longer formed on the embankment but on the filter. As the slope of the toe filter is steeper, there is a reduction in the seepage and the level of water at the end of the dam.

4.2.3 The Effect of the Permeability of Filter Material

In this part of the study, the effect of the permeability of the toe filter material on the seepage behavior has been tried to be understood. Three different permeability values, 10^{-2}, 10^{-3}, and 10^{-4}, were determined and as the permeability decreased, the seepage behavior in five different sections of the dam was investigated. For 27 varied dam designs consisting of groups of three such as T101-T104-T107, the permeability value decreased as the value of the dam code increased. In other words, T101 coded dam has 10^{-2} permeability value while T107 coded dam has 10^{-4} permeability value. In the first stage, the behavior of seepage in the dam sections was examined, followed by the analysis of the water head in the dam sections.

The change in the permeability of the dam filter material did not cause a serious effect on the first section of the dam. In Section 2, as the permeability of the filter decreased, there were fluctuations in the seepage. There is no clear pattern to these increases and decreases, which are not substantial. It is seen that this seepage behavior continues in Section 3. Only in the T120-T123-T126 dam group was there a high degree of variation in the seepage. And it is not possible to explain the reason for this with a general inference. The analysis needs to be made specific to the dam and is not within the scope of this study.

Figure 4.14. Maximum Seepage in Sections for the Change in the Permeability of Filter Material

In Section 4, different seepage behaviors can be observed. It is seen that fluctuations in the seepage increase as the position of the section gets closer to the toe filter. When dams with a code greater than 155 are compared to those coded T155-T158-T161, their seepage characteristics show a similar pattern. The reason for this is that the filter of these dams has a long horizontal length and the section is close to the filter. The decrease in the permeability of the filter material has led to a decrease in the seepage in these varied dam designs, as expected. In other varied dam designs, small increases and decreases were observed in the seepage. According to the graph of the last section, the reduction in the permeability of the filter material significantly reduces the maximum seepage. The reason why almost all dams exhibit the same behavior is that seepage now continues above the filter material. It is expected behavior that seepage will decrease as permeability decreases.

Based on the graph presented in Figure 4.14, the change in water head can be observed in these sections of a homogeneous toe-filtered embankment dam when the permeability of the filter material is reduced. The water head is not significantly affected by the decrease in permeability in Section 1 and Section 2. For section 3, there is a regular decrease in water head for dam group T173-T176-T179. The reason for this could not be determined with the data within the scope of the study and requires a detailed analysis of the dam. Aside from this exceptional case, the change in permeability in the first three sections of the dam does not contribute significantly to the water head in these sections. The results of the analysis performed on 27 different dams for Section 4 show that the change in the permeability of the filter material has different effects on different dams. Some dams do not experience any change in water head as a result of the change in permeability. In the remaining dams, the water head in the section first decreased and then increased again. Therefore, it is impossible to describe a general pattern of behavior.

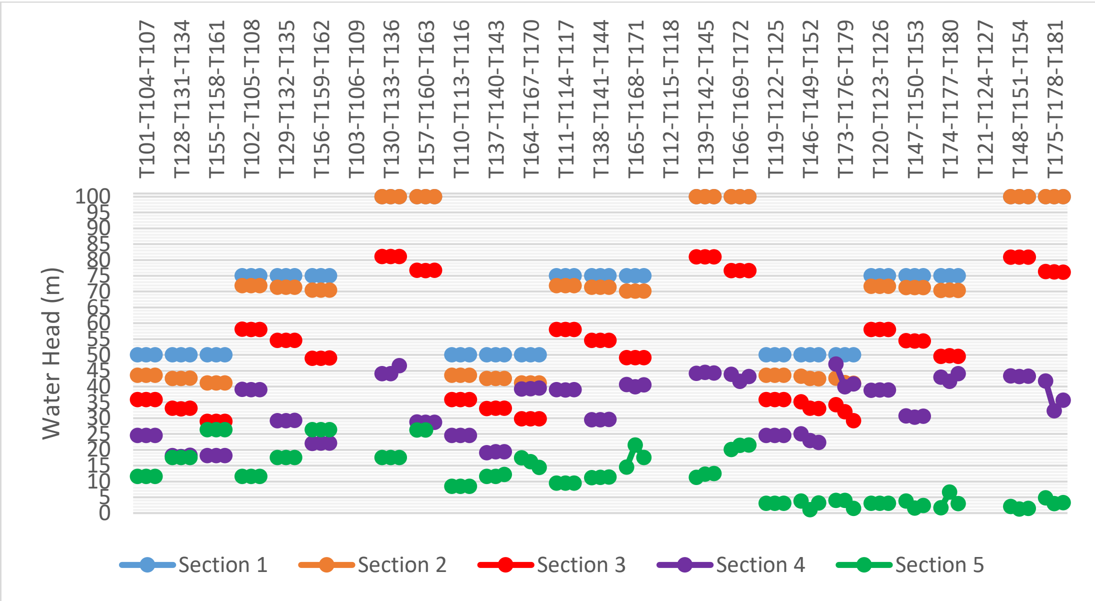


Figure 4.15. Water Head in Sections for the Change in the Permeability of Filter Material

The plot of Section 5 also shows similar results to Section 4. To summarize, the effect of permeability on the seepage in the dam body is not serious in the first three sections and does not show a regular increase or decrease. The seepage decreased with the decrease in permeability in the sections of the dam adjacent to or above the filter. It does not have a significant effect on the water head in the dam body in the sections upstream, however, it causes a different pattern of behavior in the downstream portion of the dam. It is not possible to make general inferences about these behaviors and should be analyzed in the context of the dam in question.

When the effect of the change in permeability on seepage is mentioned, as the similarities and differences in terms of toe filter and blanket filter, it is seen that Section

1 and Section 2 exhibit similar behavior in terms of seepage. Starting from Section 3, changes in the seepage are sharper in blanket filter dams. Toe filter dams exhibit similar seepage behavior in Section 5, whereas blanket filter dams behave differently and unpredictably. From the water head point of view, it is seen that the first three sections give similar results in terms of both filter types. In the last two sections, the effect of the change in permeability in the blanket filter is almost negligible, while the effect in toe filter dams varies from dam to dam and should be analyzed and interpreted.

4.2.4 The Effect of the Length of the Toe Filter

The last parameter to investigate the impact of the toe filter on seepage behavior is the horizontal length of the filter. The values of 50 m, 100 m, and 150 m were chosen as filter lengths. For the given five sections of the dam, as in the previous sections, the seepage and the water head in the section were examined. The dams were classified as three for three different lengths, and the analysis results were compared for 27 varied dam designs.

When Section 1 is examined, it is seen that increasing the length of the toe filter increases the seepage in this section. Although this increase was not significant, it was seen at different rates according to the variation of dam design. Section 2 draws a different picture from the first section. While dams such as T114-T141-T168 continue to increase regularly, there are also dams with regular decreases such as T126-T153-T180. In some dams, fluctuations are observed in the seepage rather than a regular increase or decrease. It can be seen in the graph that the fluctuations seen in the previous section are similar to Section 3. In this section, the fluctuations in the amount of flow are also relatively minor. Even though the presence of a 50 m toe filter for the T123-T150-T177 dam design results in a substantial increase in the seepage, it is not possible to explain this behavior merely by considering the general features of the dams themselves. The reason for this should be determined by a detailed analysis of the dam and is not within the scope of this study. In the graph for Section 4, it is seen that radical increases in the seepage begin to be seen with the increase in toe length. The common feature of the dams showing this radical increase is that the filter slope is 60 and this increase is seen when the filter length changes from 100 m to 150 m. For these dams and many other dams, a decrease in the seepage in the section is observed as the filter length changes from 50 m to 100 m. However, some dams do not exhibit this behavior or whose variable increases and decreases are not significant. Section 5 shows that increasing the length of the toe filter alters the seepage at different rates depending on the variation of dam design, and it is difficult to draw general conclusions from this graph.

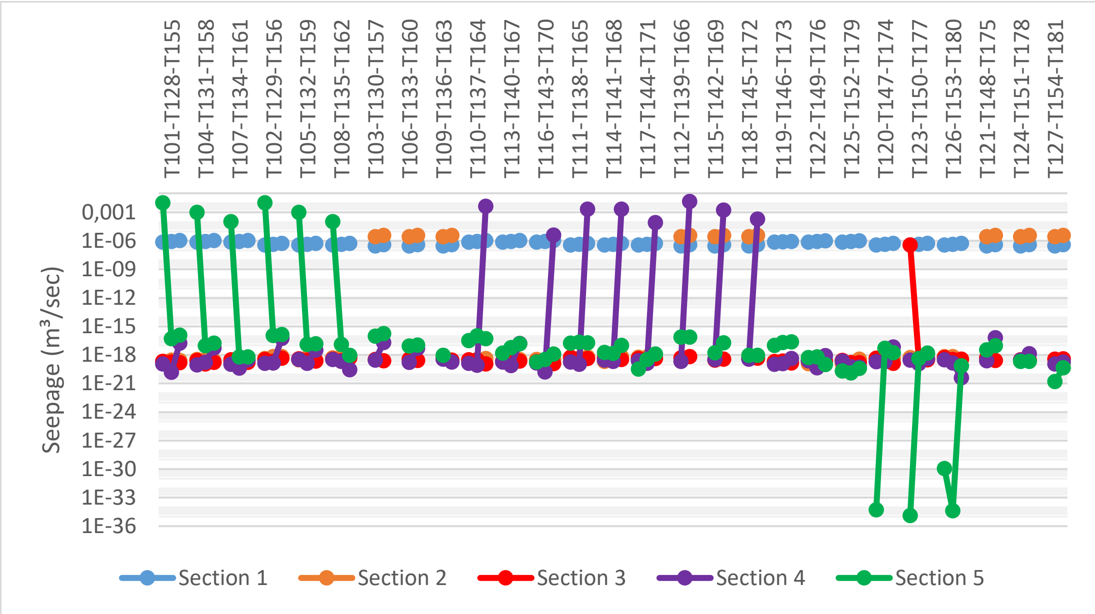


Figure 4.16. Maximum Seepage in Sections for the Change in the Length of the Toe Filter

Figure 4.16 illustrates how the toe filter length affects the water head in the dam sections. In Section 1, it is seen that increasing the filter length does not affect the water head. For many dams from Section 2, it is seen that as the filter length increases, the water head in the section decreases. The clearest illustration of this proposal can be found in Section 3. Although it is seen that increasing toe filter length in the first three sections causes similar behavior patterns, the situation is slightly different for Section 4 and Section 5. In Section 4, two different dominant behaviors are observed. In the first behavior, as the filter length increases, the water head in the cross-section decreases regularly. In the other behavior, the water head first decreases and then increases. For Section 5, contrary to other sections, it is analyzed that increasing the horizontal length of the drainage increases the water head in this section. Since there are dam groups that exhibit different behaviors from this one, it is difficult to make a general statement regarding these two sections.

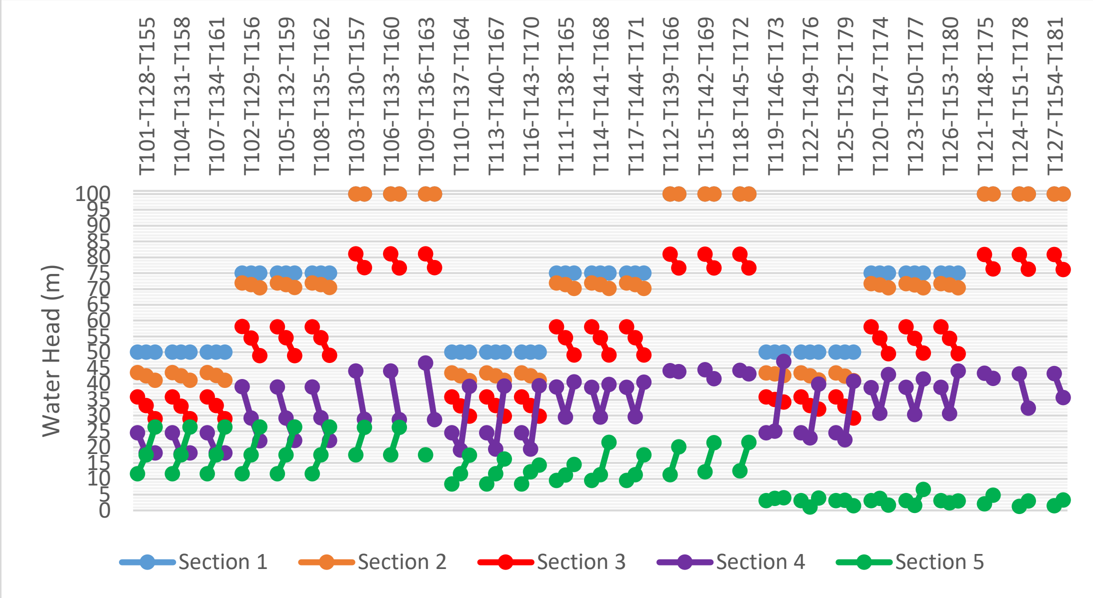


Figure 4.17. Water Head in Sections for the Change in the Length of the Toe Filter

In summary, the increase in the horizontal length of the toe filter causes a small change in the seepage. It is not possible to determine a general pattern of behavior as these changes result in different outcomes for different dams. Likewise, the effect on the water head in the sections is different for different dams. The effect is, however, more pronounced and is occurring at higher rates, as opposed to the seepage.

4.2.5 Phreatic Lines of Dams with Toe Filter

If the behavior of the phreatic line in dams with toe filters is analyzed, it can be observed that certain dams perform better than others under specific conditions. For instance, in the first four sections with a 50 m reservoir water head, the best results are obtained with the dam coded T125. This dam is a toe filter dam with a horizontal length of 50 m, a 90-degree angle with the ground, and a permeability coefficient of 10^{-4}. Similar performance is exhibited by dams coded T119 and T122. Interestingly, the only variable in these three dams is the filter permeability coefficient, suggesting that the permeability of the filter material does not have a significant effect on the phreatic line. Finally, for the last section, the best performance is demonstrated by the dam coded T167. For a water head of 50 m, the dam with the code T173 was identified as having poor performance. The dam is a toe filter type with a horizontal length of 150 m, a 90-degree angle with the ground, and a permeability coefficient of 10^{-2}. The reason for its poor performance is that the water head increases significantly in the section starting from Section 3.

Similarly, in the first four sections with a 75 m reservoir water head, the best performing dam is the one coded T126. This dam is a toe filter dam with a horizontal length of 50 m, a 90-degree angle with the ground, and a permeability coefficient of 10^{-4}. Other dams that exhibit similar performance are coded T120 and T123. The permeability of the filter material has minimal impact on the phreatic line. For the last section, the dam coded T168 performs the best. On the other hand, for a water head of 75 m, the dam with the code T180 was identified as having the poorest phreatic line behavior. This dam is also a toe filter type with a horizontal length of 150 m, a 90-degree angle with the ground, and a permeability coefficient of 10^{-4}. The reason for its poor performance is the same as the dam coded T173.

The best results in the first four sections with a 100 m reservoir water head are obtained with the dam coded T127. This dam is a toe filter dam with a horizontal length of 50 m, a 90-degree angle with the ground, and a permeability coefficient of 10-4. Similar performance is exhibited by dams coded T124 and T121. The permeability coefficient is the only variable in these three dams. For the last section, the dam coded T178 performs the best.

Finally, for a water head of 100 m, the dam with the code T118 was determined as having the worst phreatic line behavior. This dam is also a toe filter type but has a shorter horizontal length of 50 m, a 60-degree angle with the ground, and a permeability coefficient of 10^{-4}.

In summary, the analysis of dams with toe filters reveals consistent patterns in phreatic line behavior. Dams like T125, T126, and T127 consistently perform well, while T173, T180, and T118 consistently exhibit suboptimal behavior. These findings underscore the importance of tailoring dam designs to specific conditions for optimal phreatic line outcomes.

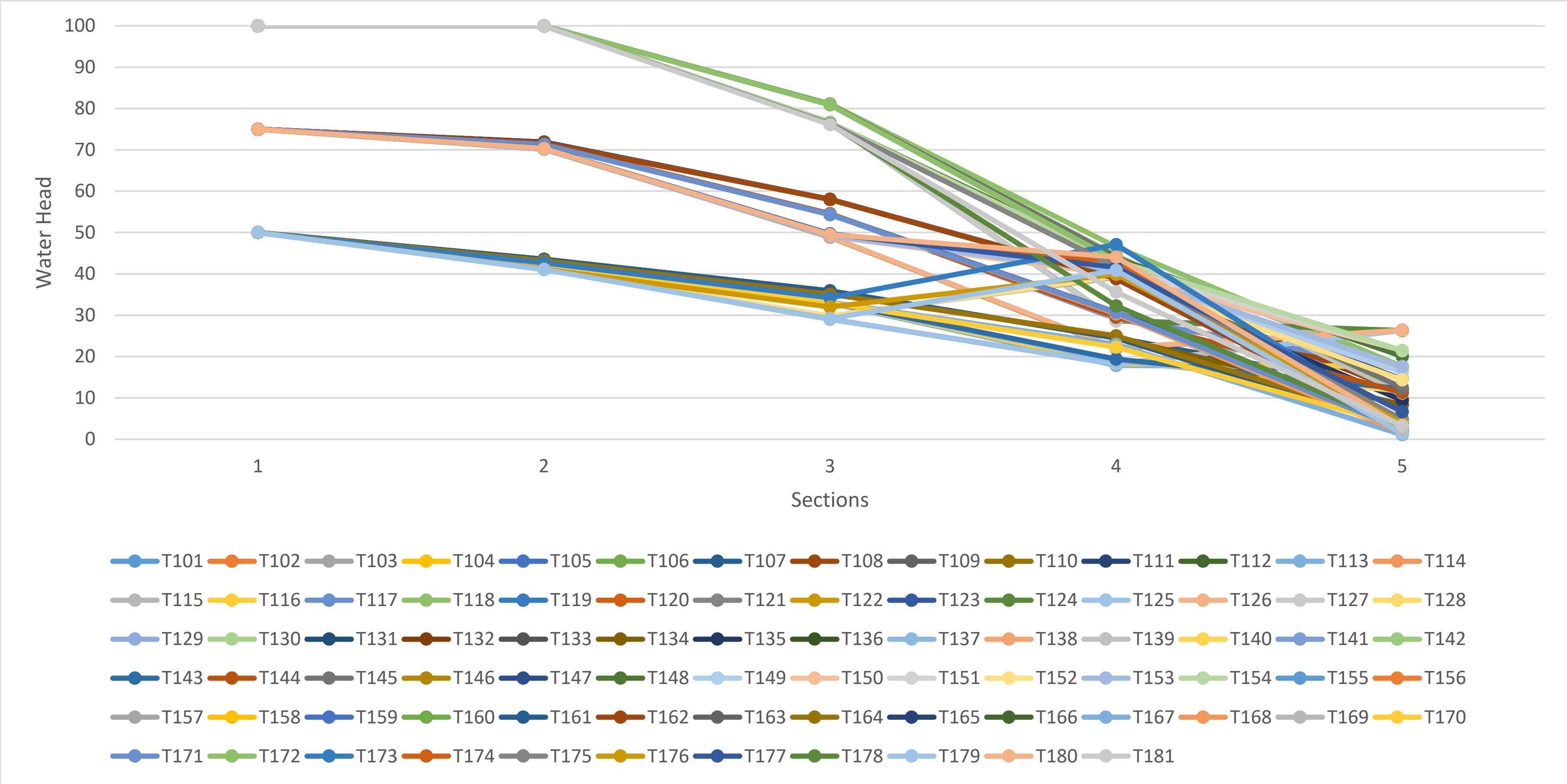


Figure 4.18. Phreatic Lines for Dams with Toe Filter

4.3 Chimney Filter

Another filter type used in this study was determined as a chimney filter. As previously determined in the blanket filter and toe filter, in this study, the effect of the change of four different parameters on the seepage and water head in different dams was tried to be analyzed. The water head in the reservoir, the thickness of the filter, the permeability of the filter material, and the height of the chimney filter from the base of the dam are the parameters that are evaluated in the study. There are 81 completely different dams designed with three different values for these four different parameters. For the purpose of distinguishing these dams in analyses performed with SEEP/W, they are identified by the code C1XX. Comparing the maximum seepage and the maximum water head data on five different sections of each dam determined to be permanently fixed in the body of the dam was conducted to gain an understanding of the seepage behavior of the dams as a function of the changing parameters.

4.3.1 The Effect of the Water Head

In this part of the study, the effect of the increase in the reservoir water head on the seepage behavior of a chimney filter dam is tried to be understood. It was determined that 27 varied dam designs would be analyzed, with a reservoir head of 50m, 75m, and 100m, respectively, and the results of the analyses were plotted over the dam groups. As the numerical value of the dam name increased in the groupings, the head of the reservoir also increased. As shown in Figure 4.17, C101-C102-C103 represents one of 27 varied dam designs, and the water head in the reservoir increases from 50 meters to 100 meters as it moves from C101 to C103.

Another point that should be known before interpreting the graphs is that these analyses were made on 5 different sections of the dam body: Section 1, Section 2, Section 3, Section 4, and Section 5. These five sections are located 100m, 200m, 300m, 400m, and 500m from the upstream toe of the dam, respectively. Then, for each section, first, the seepage and then the water head graphs in the section were drawn.

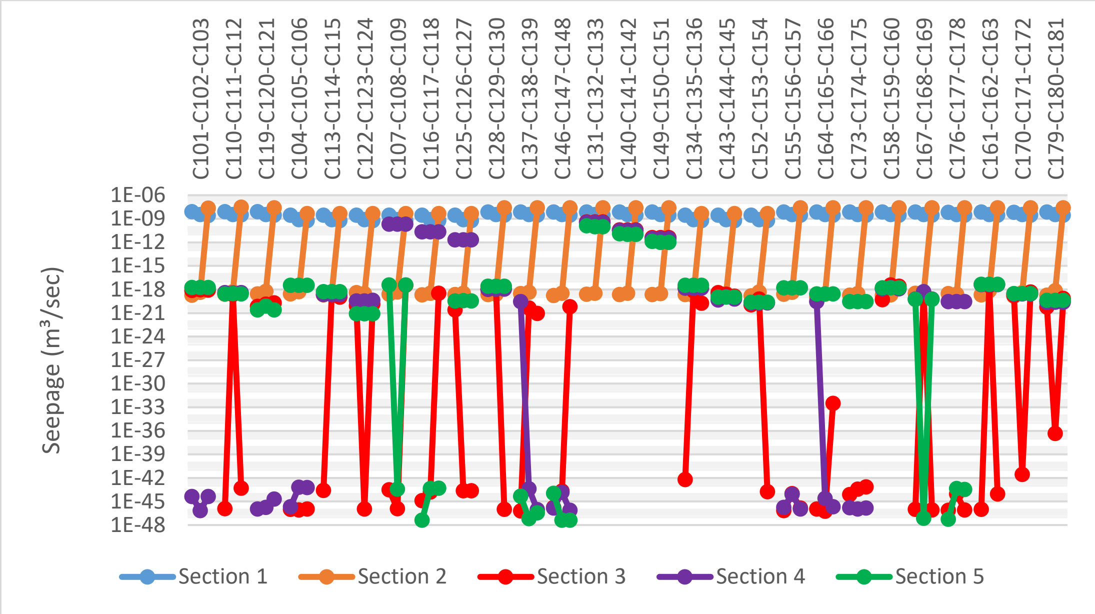


Figure 4.19. Maximum Seepage in Sections for the Change in the Water Head

The results of the analysis for the first section of 27 varied dam designs show that the increase in the water head in the dam reservoir reduces the seepage in this section. Although the amount of this decrease is different for different dams, the general attitude is similar for each dam. Based on the analysis of Section 2, it can be seen that the seepage behavior of Section 2 differed from that of Section 1. The general behavior is a slight increase in the seepage in the section as the reservoir head increases from 50m to 75m. However, the transition from 75m to 100m has increased the seepage in this section significantly. Exceptionally, in a few dam groups such as C176-C177-C178, a slight decrease was observed in the seepage instead of an increase in the reservoir water head during the transition from 50m to 75m. The reasons for this change require analysis specific to the variation of dam design and are beyond the scope of this study. While similar behavior is observed for 27 varied dam designs in the first two sections, different seepage behaviors are analyzed in Section 3. On the one hand, there are dams such as C101-C102-C103 where there are small increases and decreases in the seepage. On the other hand, there are groups such as C110-C111-C112 where increases and decreases occur more sharply and simultaneously. These variable behaviors indicate that the increase in reservoir level in Section 3 causes different seepage activity in different dams. Therefore, it is not possible to predict seepage behavior in this section of any dam and requires dam-specific analysis.

According to Section 4, the reservoir head increases without causing any changes in the seepage. Apart from these, there are dams in which small increases and decreases in the seepage are observed, and dams such as C137-C138-C139 where the increase in the reservoir level causes a sharp and regular decrease. The seepage of most of the dams in Section 5 does not change. Similarly, some dams exhibit exceptional behavior with varying degrees of increase and decrease.

This part of the study aims to brighten to effect of the increase in the water head of the reservoir in the dam body. For the same five sections of different 27 dams, the water head in the dam body was investigated and the impact of the increase in reservoir head tried to be understood. The first two sections which were modelled in Figure 4.18 visualized the effect of the increase of reservoir head in the sections. Every dam group (as an example C101-C102-C103) in the graph shows that for the first two sections increase in reservoir level causes an increase in water head in Section 1 and Section 2. This behavior repeats itself for different 27 varied dam designs. However, in Section 3 this regular behavior commences changing.

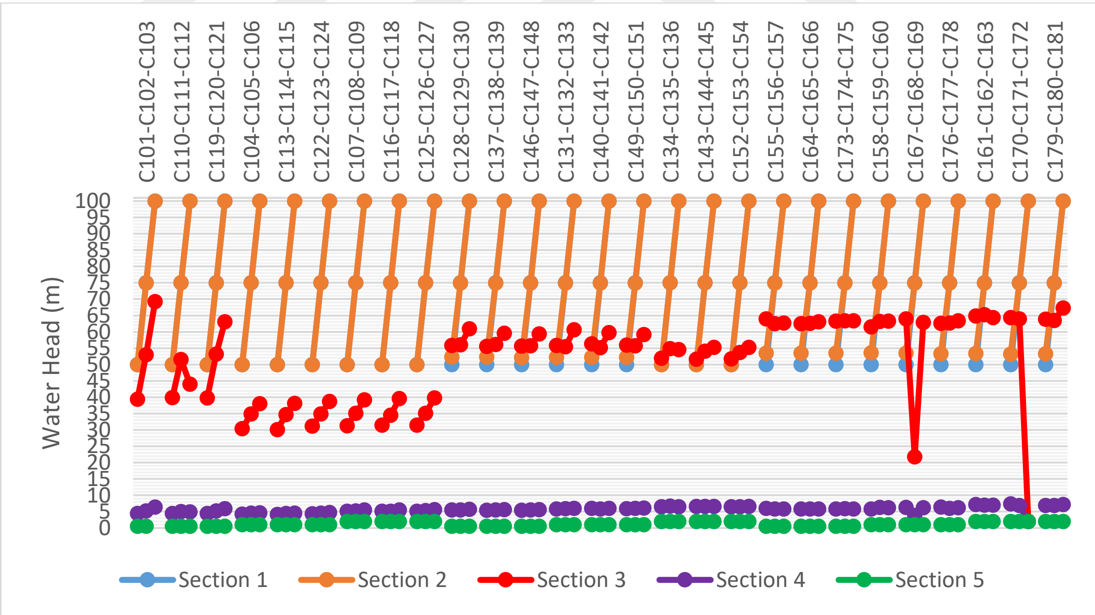


Figure 4.20. Water Head in Sections for the Change in the Water Head

In Section 3, varied dam designs show different attitudes to the increase in reservoir heads. As an example demonstrated in Figure 4.18 for the dam design C104-C105-C106, regular increase in water head with the increase in reservoir level continues, on the other hand, for the dam design C173-C174-C175 that increase shows itself more slightly. The reason for these behaviors should be investigated specifically for each dam. Nevertheless, by examining the analysis results of this and previous filter types, the common belief that the increase in reservoir head increases the height of the water in the dam body can be dispelled. It can be said that the effect of the increase in the reservoir head on the water head in the dam body causes a different increase and rarely a decrease in varied dam designs. The analysis results given in Section 4 also support this statement. As can be seen in Section 5, the change in the reservoir head has no significant effects on this section. There is an equal relationship between the water head in the section and the thickness of the filter in all variations of the dam design.

Based on the data obtained for five different sections of chimney filter embankment dams at three different reservoir levels, it can be concluded that although seepages in the sections of chimney filter embankment dams are similar for the first two sections, the amounts of seepage in the third section differ between dams due to differences in the amounts. This sharply variable behavior is replaced in the last two sections by more subtle changes in the seepage. As noted above, the water head in dam sections exhibits similar behavior for all varied dam designs in the first two sections, however, the third and fourth sections require analysis specific to the dam design itself. In the last section, the water head for all dams is equal to the filter thickness.

4.3.2 The Effect of the Chimney Thickness

The objective of this research is to analyze the impact of variations in chimney thickness on seepage and water heads in dam structures. The dams under consideration are classified as C101, C104, and C107, with corresponding chimney thicknesses of 50 cm, 100 cm, and 200 cm. As the number in the dam code rose, the thickness of the dam filter also increased. By utilizing SEEP/W software, 27 varied dam designs were modelled, with specific attention paid to five distinct dam sections, namely Section 1, Section 2, Section 3, Section 4, and Section 5. These sections are segmented into 100-meter intervals, commencing from upstream and extending downstream.

According to the first section of the dam, the thickness of the filter resulted in different seepage rates as the filter thickness was increased. Some dams, such as C156-C159-C162, were not significantly affected by variances in filter thickness. However, as can be seen in Figure 4.19, for some dams an increase in the filter thickness from 50 cm to 100 cm decreased seepage. Other dams have demonstrated this decrease by increasing their filter thickness from 100 cm to 200 cm. Similarly, in Section 2, seepage displays irregular increases and decreases. Based on the analyses of the first two sections of the dam, it has been determined that there is no regular pattern between the seepage and the thickness of the filter. The first two sections of the dam experienced a marginal change in seepage rate upon an increase in the filter section. However, the seepage fluctuations did not demonstrate a consistent pattern, indicating that each dam exhibits a distinct reaction to such conditions. For Section 3, Section 4, and Section 5, the graph reveals that the dam's response to the alteration in filter thickness persists in these sections as well. Unlike the first two sections, the increase in chimney filter thickness in these sections led to sudden changes in the seepage. While some dam groups exhibited similar behavior in terms of seepage variance, it is imperative to examine each dam to comprehend this pattern from a broader perspective.

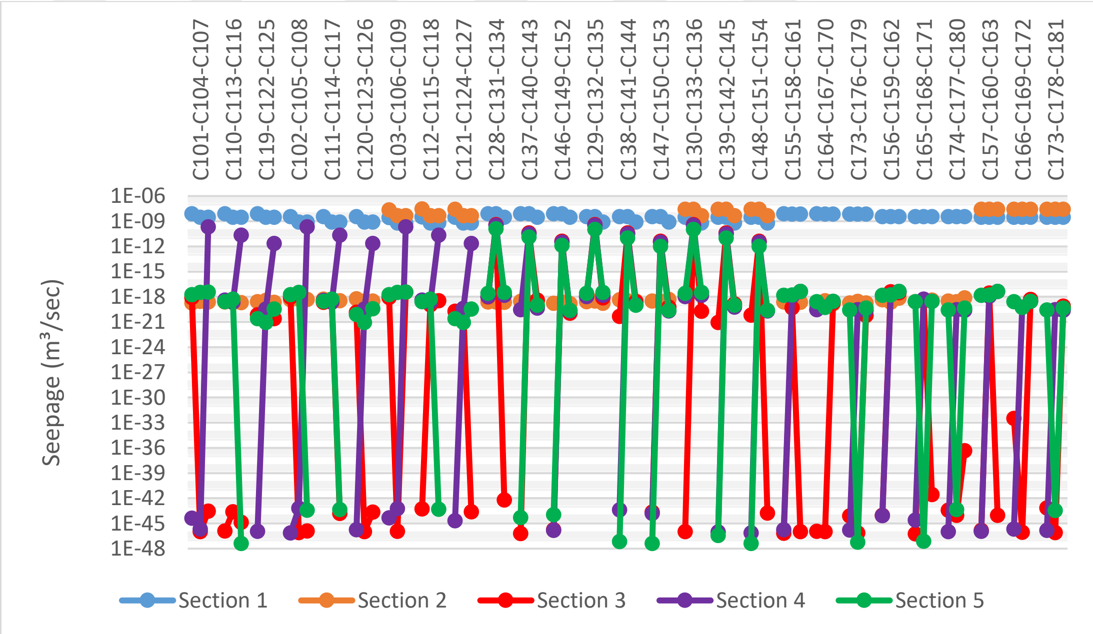


Figure 4.21. Maximum Seepage in Sections for the Change in the Chimney Thickness

In summary, comprehending the impact of the increase in chimney filter thickness on seepage in a dam body requires analyzing each dam individually. The effect of the increase in filter thickness on seepage varied across different dams, resulting in an increase in some and a decrease in others. As such, it is not viable to draw a general conclusion about seepage behavior in dams with chimney filters based on these findings.

To better understand the impact of the increase in filter thickness, it will be investigated the water head in the dam body for the same varied dam designs. The varied dam designs were grouped into three with corresponding chimney thicknesses of 50 cm, 100 cm, and 200 cm, and the results were graphed for Section 1, Section 2, Section 3, Section 4, and Section 5, as shown below. Figure 4.20 displays the water head graph for all sections. Notably, Section 1, situated 100 meters away from the upstream toe of the dam, remained unaffected by any alterations in the water head. Conversely, in Section 2, the water head experienced minor changes as the thickness of the chimney filter increased. It is worth mentioning that varied dam designs such as C128-C131-C134 showed a more pronounced change in water head. It is pertinent to note that the reason for this behavior will not be discussed in this thesis to ensure that it does not detract from the main subject matter.

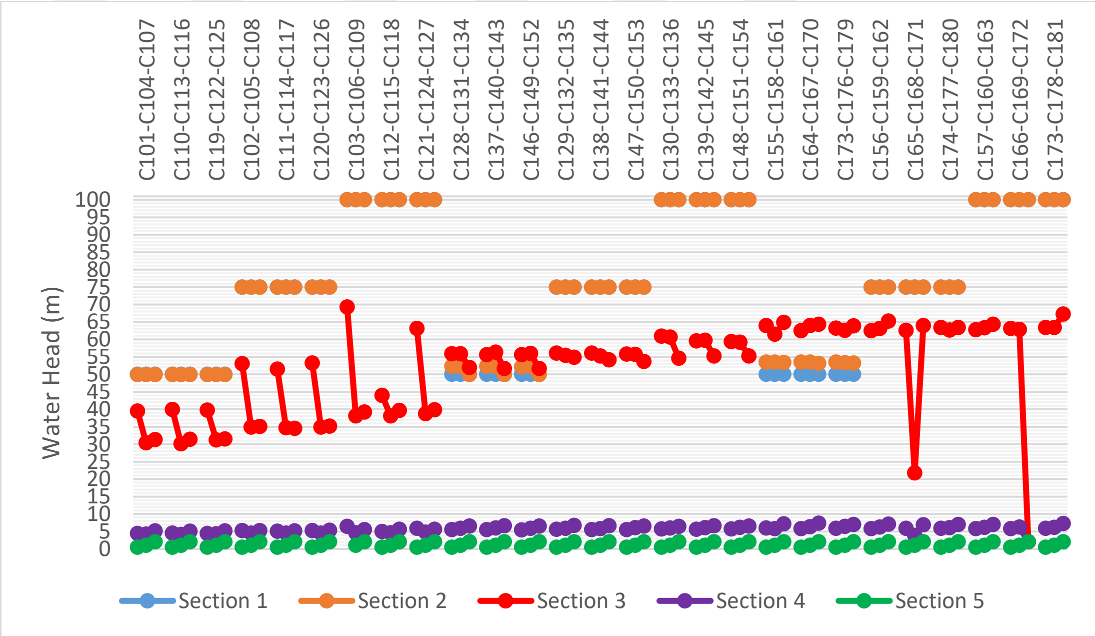


Figure 4.22. Water Head in Sections for the Change in the Chimney Thickness

In contrast to the initial two sections, the third section showcases a more apparent effect of the increase in the chimney filter section on the water head in the dam body. Specifically, in dam design C101-C104-C107 and a few other varied dam designs, the water head in the section experiences a significant decrease as the thickness increases from 50 cm to 100 cm. However, during the transition from 100 cm to 200 cm, this decrease leads to an increase in the water head in the section, albeit a slight one. It is important to note, however, that this pattern does not apply to all varied dam designs.

In some varied dam designs, an initial increase in the water head in the section is observed, followed by a decrease. In other cases, the graph indicates a constant decline in the water head in the section. Consequently, it would not be appropriate to draw general conclusions about dam behavior for these sections.

In Section 4, it is observed that two distinct designs of behavior prevail for the water head. The first design illustrates that as the chimney thickness increases, the water head in the section initially decreases, followed by a subsequent increase. On the other hand, the second design demonstrates that the water head in the section continuously increases. To gain a better understanding of the reasons why two different situations arise, it would be beneficial to determine which situation occurs in each dam. However, this study does not perform such analysis. The graph presented for Section 5 indicates that in all dams except for the C109 dam that failed, the water head reaches the same level as the thickness of the filter in this section. Given that this behavior occurs in all different dams, it can be concluded that the water head in the downstream toe part of the dam increases in parallel with the increase in the chimney filter thickness.

To summarize all the findings, a dam-specific analysis is necessary to comprehend the effect of filter thickness in a dam with a chimney filter on the seepage in the dam body. Based on the findings, it would be incorrect to generalize the response of dams to this change and draw a pattern. However, concerning its effect on the water head in the dam body, it would be appropriate to make the following comment: for a dam with a chimney filter, as the chimney filter thickness increases, the water head in the downstream toe part of the dam will increase. For other parts of the dam body, different types of behavior can be observed in the water head.

4.3.3 The Effect of the Permeability of Filter Material

This section of the study aims to analyze the impact of decreasing filter material permeability on the seepage in an embankment dam with a chimney filter. Additionally, the study aims to examine the changes in the water head in the dam body. To carry out this analysis, 27 varied dam designs were evaluated, and three different permeability values were determined for each. Triple group codes were assigned to dams with these three different permeability values. For instance, the first group, identified as the C101-C110-C119 trio, had all features kept constant except for the dam-design filter permeability. The simulation showed that as the value in the code of the dam increases within the groups, the permeability value decreases. The dam filter coded C101 has a permeability value of 10^{-2}, while the dam coded C110 has a permeability value of 10^{-3}, and the dam coded C119 has a permeability value of 10^{-4}.

In the course of the analyses conducted on these dams, a comparison was made among the results obtained from five distinct sections of the dam. The first section, namely Section 1, is situated at a distance of 100 m from the upstream toe of the dam, and the other sections are placed at 100 m intervals from the preceding section. In other words, Section 2, Section 3, Section 4, and Section 5 are positioned at a distance of 200 m, 300 m, 400 m, and 500 m, respectively, from the upstream toe of the dam. The study sought to evaluate how the alteration in chimney filter permeability impacted the maximum seepage and water head values for each section.

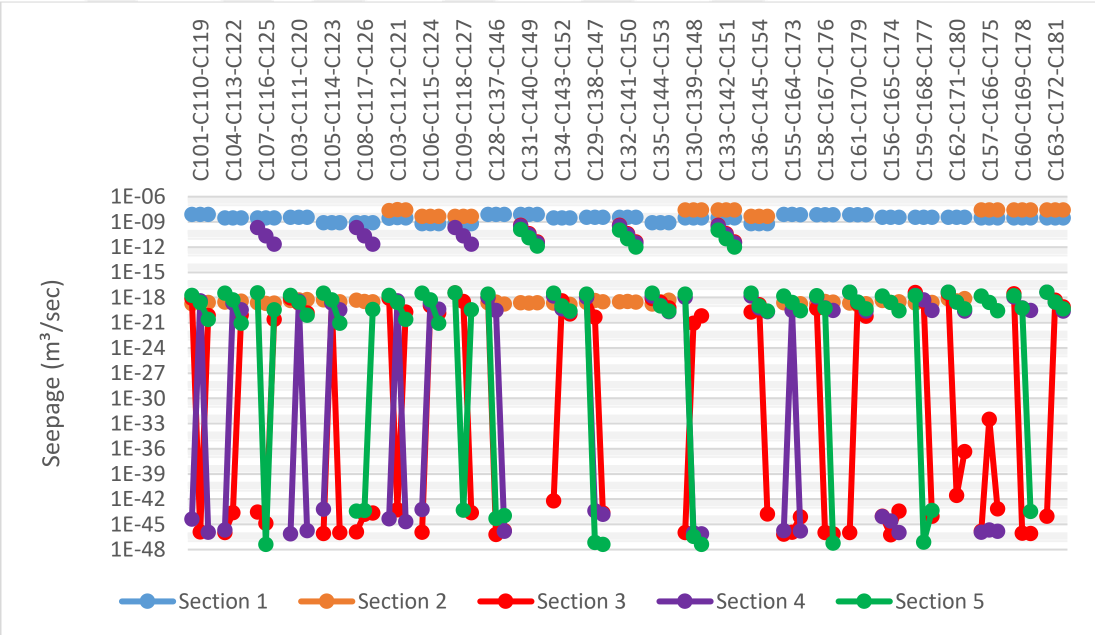


Figure 4.23. Maximum Seepage in Sections for the Change in the Permeability of Filter Material

Based on Figure 4.21, it can be observed that the decrease in permeability of the chimney filter has no significant impact on the seepage in the first two sections of the dam, at the given rate. The first section was virtually unaffected, while the second section showed minor irregularities in terms of increase and decrease. However, the third section, as depicted in the graph, exhibited a different pattern than the previous two sections. Although some dams, such as C102-C111-C120, showed a regular and gradual decrease in seepage, others, such as C105-C114-C123, showed a sharp decrease and increase simultaneously. The reason for this distinct seepage behavior requires further investigation through a comprehensive study specific to the dam, which is beyond the scope of this analysis.

The graph analysis suggests that the permeability of the chimney filter has varying effects on the seepage in different dams, with Section 3 displaying the most visible effects. The graphs for Section 4 and Section 5 indicate that this behavior leads to a consistent reduction in the seepage for most of the dam design. However, there are certain varied dam designs where sharp increases and decreases occur simultaneously. Based on the available data, it can be concluded that a reduction in filter permeability in a dam with a chimney filter does affect the seepage in the dam body. However, it would be incorrect to generalize this effect and conclude that it leads to a regular increase or decrease in seepage.

The methodology described above entails an analysis of the impact of the change in chimney filter permeability on the dam body. This will be achieved by examining the water head in the sections for the same varied dam designs and the same sections. The graph presented in Figure 4.22 for Section 1 and Section 2 demonstrates a parallel relationship with the seepage. The results indicate that the decrease in filter permeability does not have a discernible effect on the water head in either section. Once again, the graphical representations in Section 3 and Section 4 demonstrate how the change in filter permeability is affecting the existing dam section. Although the shift in water head across the sections is not as pronounced compared to the change in seepage for most dams, irregularity is evident in both parameters. Specifically, in C103-C112-C121 and a few other varied dam designs, there is initially a sharp decrease followed by a sharp increase. This particular modification presents a challenge in establishing a consensus.

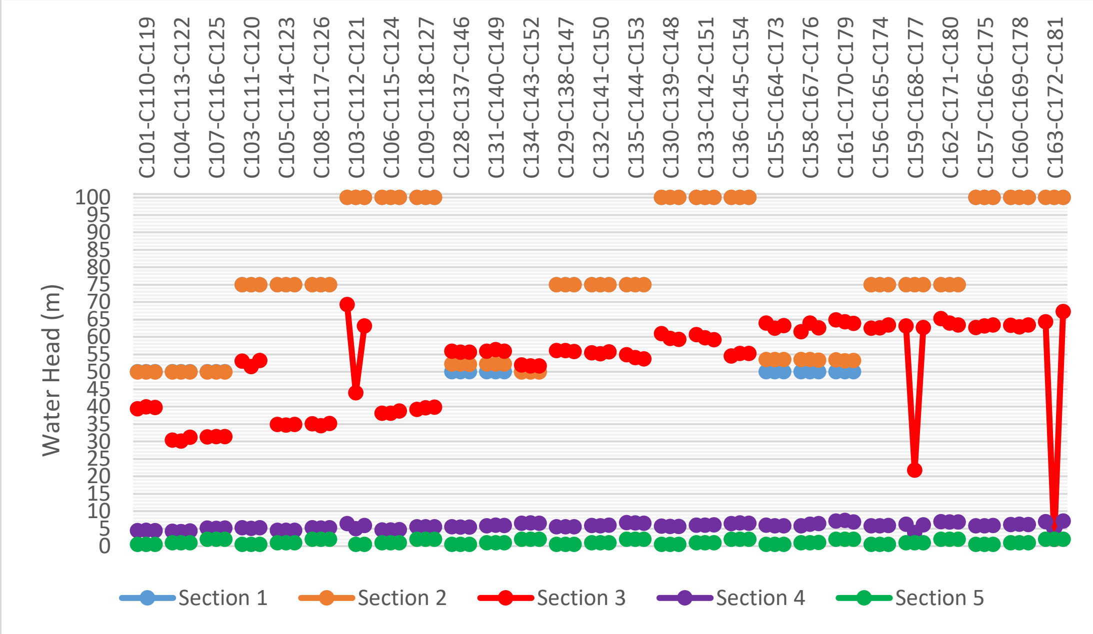


Figure 4.24. Water Head in Sections for the Change in the Permeability of Filter Material

Based on the analysis conducted for the last section of the dam, it can be observed that the impact of any alteration in the permeability of filter material is comparable to the results derived from the first two sections of the dam. In the last section, the water head is almost equalized to filter thickness and minor changes may be observed in the water head for certain varied dam designs.

To summarize, variations in the permeability of filter material in the ratio of 10^{-1} cause a slight increase and decrease in the seepage for Section 1 and Section 2. However, in the other sections, the behavior of seepage begins to fluctuate, and sharp increases and decreases are evident. It has been ascertained that there are no significant changes in the water head within the dam body in the first two and last sections as permeability decreases. However, in Sections 3 and 4, high increases and decreases are observed simultaneously in some varied dam designs. Furthermore, another finding obtained from the analyses conducted in this section is that there exists no linear relationship between permeability and seepage and water head.

4.3.4 The Effect of the Height of the Chimney Filter

In this part of the study, an analysis was conducted to determine the impact of changes in the vertical length of chimney filters on the seepage and water head in the dam body.

The dams were designed with three different filter heights: 50m, 75m, and 100m, and were grouped in threes, such as C101-C128-C155, based on increasing filter height. A total of 27 varied dam designs were analyzed in five different sections: Section 1, Section 2, Section 3, Section 4, and Section 5. These sections were located at 100m, 200m, 300m, 400m, and 500m from the upstream toe section of the dam. Graphs were provided to show both the seepage and the cross-sectional water head for each section.

Upon examination of the seepage graph from the first section of the dam, it can be observed that three distinct behaviors prevail. In certain dams, increasing the chimney height does not yield a significant impact on the seepage within the dam structure. Secondly, while there is an increase in the seepage as the chimney height increases from 50 m to 75 m, no significant effect is observed when increasing from 75 m to 100 m. Thirdly, while there is no significant change in the seepage from 50 m to 75 m, an increase in the seepage can be observed as the chimney height increases from 75 m to 100 m. For the second section, it can be observed that the impact of an increase in chimney height on the seepage does not exhibit distinct patterns as seen in the first section. In this section, alterations in the seepage vary for varied dam designs, but the magnitude of change remains relatively gradual. The slight alterations observed in the first two sections are replaced by sharp increases and decreases in the third and subsequent sections. The effect of a steady increase in chimney height on the seepage varies for varied dam designs.

In Section 3, the maximum seepage generally occurs at a chimney height of 75 m, while in Section 4, cases where the maximum seepage is observed at both 50 m and 75 m chimney height are predominant. While there are dams in the last section where the seepage does not vary, unlike Section 3 and Section 4, there are also cases where the seepage is minimum at 75 m chimney height. Detailed analyses and comparisons can be made using graphs to speculate on the reasons for these changes specifically for dams. However, since this detailed analysis would distract from the interpretation of the general effect of the parameters on seepage, which is the main subject of the study, no detailed analysis was made in this study. A general analysis shows that, as in many other analysis results, the effect of the increase in chimney height on the seepage in the dam body is quite different for varied dam designs.

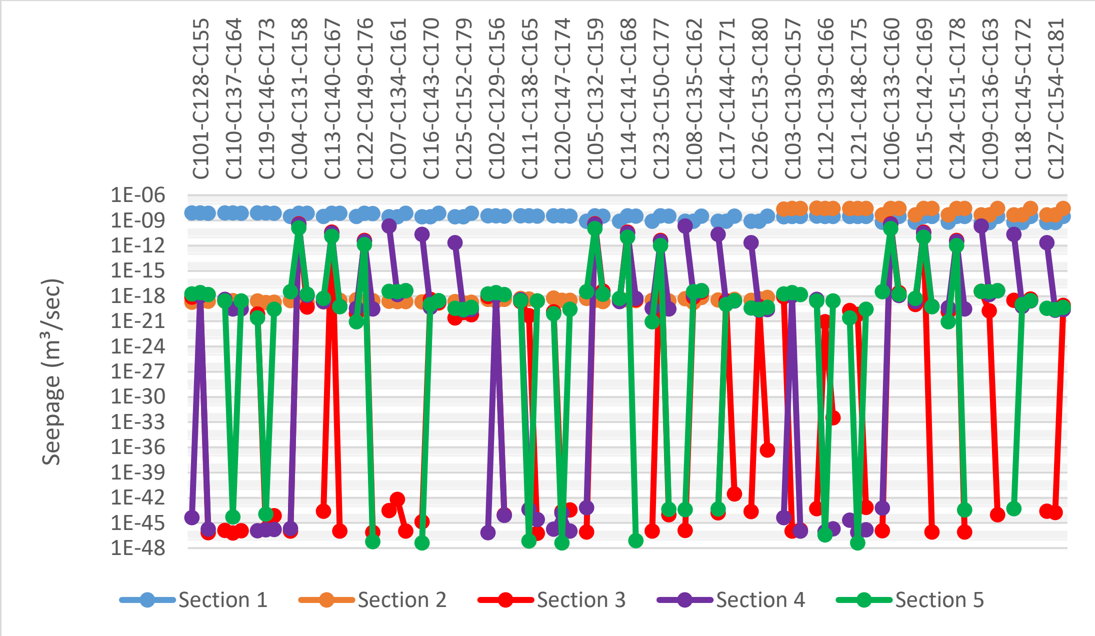


Figure 4.25. Maximum Seepage in Sections for the Change in the Height of the Chimney Filter

Upon examination of the graph for various sections, it becomes apparent that the impact of increasing the chimney height on the water head in the dam body is not uniform across all sections. Specifically, in Section 1, it appears that changes in the chimney height have no noticeable effect on the water head. While this trend continues for several dams in Section 2, there are some varied dam designs, specifically C101-C128-C155, where the water head rises proportionally with the chimney height. The graph for Section 3 and Section 4 yield similar results, indicating that the general trend is for water head to increase with chimney height. However, the degree of change is greater in Section 3 compared to Section 4. Moreover, while a general increase in water head is observed, it is important to note that there are varied dam designs with differing behaviors, such as C114-C141-C168. The underlying reasons for these differences are highly specific to each dam and, therefore, beyond the scope of this particular study. Upon closer examination last section, it becomes evident that the notion of an increase in water head being directly proportional to the height of the chimney in the dam body does not apply to this particular section. It can be observed that the water head in the section of all dams is almost equal to the thickness of their respective chimney filters.

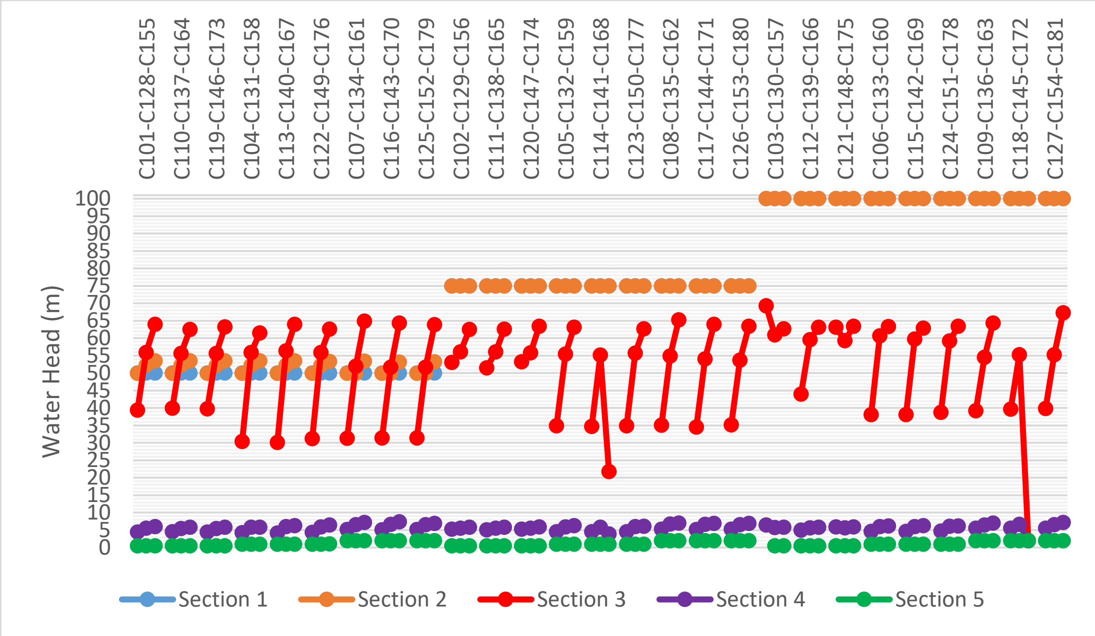


Figure 4.26. Water Head in Sections for Change in the Height of the Chimney Filter

In conclusion, the findings of this study suggest that increasing the chimney height in a dam generally results in a corresponding increase in water head, albeit with varying degrees of impact across different sections. However, it is important to note that certain varied dam designs with distinct behaviors require further investigation. The analysis of the data has revealed that there are slight changes in the first two sections and more significant changes in the last three sections regarding the seepage. Furthermore, these changes are not consistent across different dams, and there is no regular behavior parallel to the regular increase in chimney height. These findings suggest that further research is necessary to better understand the underlying factors that contribute to the observed changes in the seepage.

4.3.5 Phreatic Lines of Dams with Chimney Filter

After analyzing the changes observed in the phreatic line of zoned dam designs with chimney filters, it was determined that the dam with the C113 code demonstrated the best performance for a 50m reservoir water head. The dam features a blanket permeability of 10^{-3}, a thickness of 100cm, and a height of 50m. Similarly, dams numbered C110, C116, C119, C122, and C125 also displayed positive results, but their design parameters varied significantly.

However, dams with a chimney height of 100m showed poor results for reservoir levels of 50m. On the other hand, the dam with the C173 code displayed the worst results for the 50m reservoir water head in terms of the phreatic line. This dam features a blanket thickness of 50cm, a height of 100m, and a filter permeability coefficient of 10-4. Similarly, dams numbered C155, C158, C161, C164, C167, C170, C176, and C179 exhibited similar results.

When analyzing the changes observed in the phreatic line of chimney filter zoned dam designs, it was found that the dam with the C168 code had the best performance for a 75m reservoir water head. This dam features a blanket permeability of 10^{-3}, a thickness of 100cm, and a height of 100m. No dams exhibited results quite similar to this dam.

Conversely, the dam with the C174 code performed the worst, with a blanket permeability of 10-4, a thickness of 50cm, and a height of 100m. Dams numbered C156, C159, C162, C165, C171, C177, and C180 also displayed similar results, all featuring a height of 100m. However, it is important to note that the dam coded C168 gave the best results among dams with this reservoir height, preventing generalizations.

Finally, after analyzing the changes observed in the phreatic line of zoned dam designs with chimney filters, it was determined that the dam with the C178 code demonstrated the best performance for a 100m reservoir water head. This dam features a blanket permeability of 10^{-4}, a thickness of 100cm, and a height of 100m.

No dams exhibited results quite similar to this one. On the other hand, the dam with the C103 code performed the worst, with a blanket permeability of 10-2, a thickness of 50cm, and a height of 50m. Upon analyzing the dam coded C181, which showed the closest result to it, no connection could be found between them in terms of design principles. In conclusion, a detailed examination of phreatic line variations in zoned dam designs with chimney filters highlights varying performances across reservoir water heads.

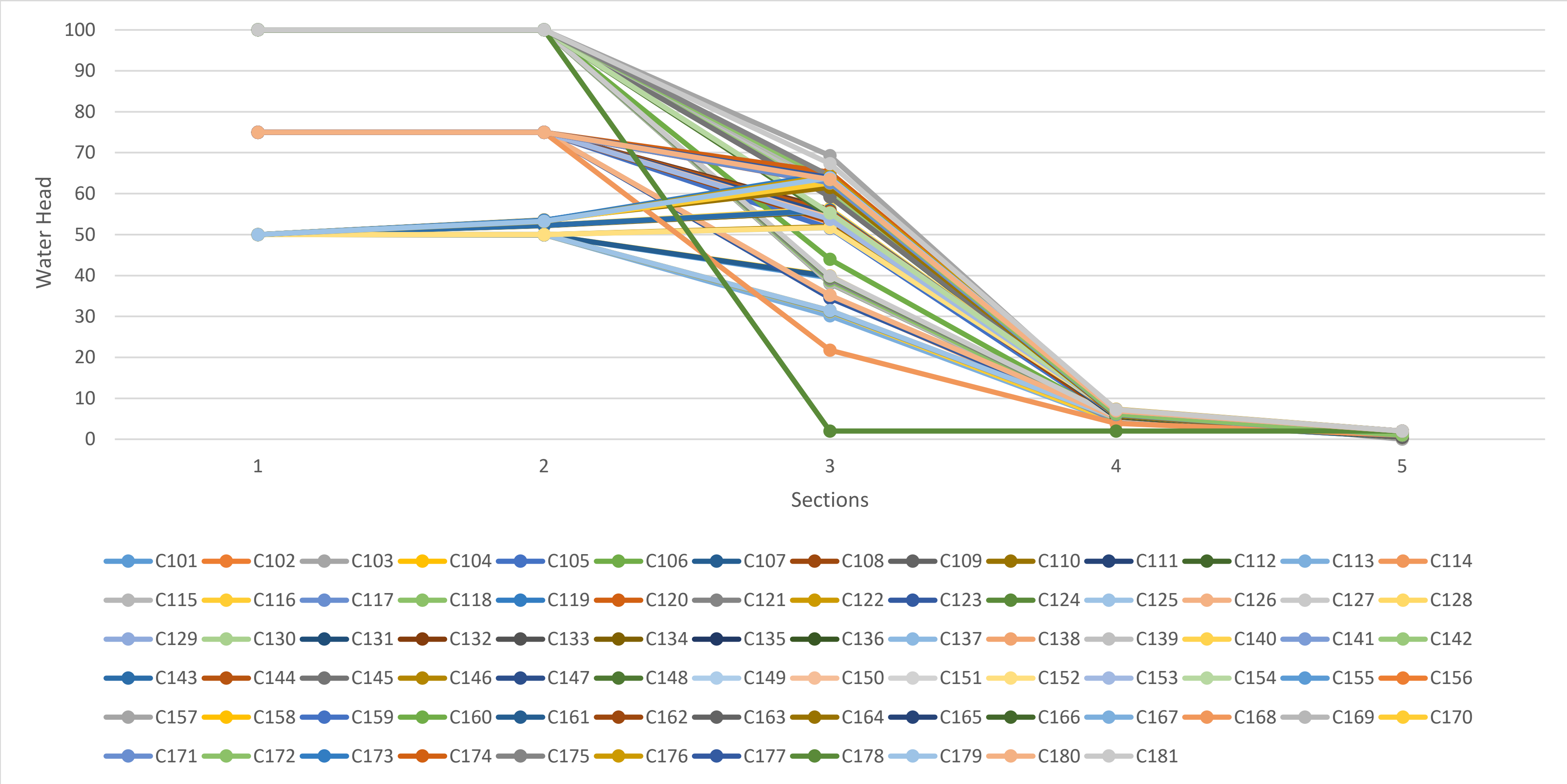


Figure 4.27. Phreatic Lines for Dams with Chimney Filter

4.4 General Summary of Results

In this section of the study, the results are summarized in Table 4.1 regarding the results of all blanket, toe, and chimney filter dams due to the changes in parameters. The general parameters that have been identified as significant in this study will be summarized, which include the effect of the increase in the reservoir water head, the consequences of the decrease in the permeability of the filter material used, and the effect of the physical changes observed in the filter structure.

This part of the study aims to provide a more detailed understanding of the behavior of filter dams under various conditions, and the results obtained from this analysis will be used to inform future decision-making. The identification of the most significant factors that influence the behavior of filter dams will be enabled by the comprehensive analysis of the various parameters identified in this study, providing insights into the optimal design and management of such structures.

Table 4.1. Summary of Results

		Increase in Reservoir Water Head	Decrease in Permeability of the Filter	Increase in Lenght of the Filter[1]	Increase in Thickness of the Filter	Increase in Slope of the Filter
Blanket Filter	Section 1	Slight decrease in seepage	No change in seepage	Slight increase in seepage	Slight changes and no change in seepage	-
		A sharp increase in water head	No change in the water head	No change in the water head	No change in the water head	-
	Section 2	A sharp increase in seepage 100 m reservoir level	Quite slight changes and no change in seepage	Quite slight changes in seepage	Slight changes in seepage	-
		A sharp increase in water head	No change in the water head	Slight decrease and no change in the water head	No change in the water head	-
	Section 3	Uncertain seepage behavior	Uncertain seepage behavior	Quite slight changes in seepage	Uncertain seepage behavior	-
		A sharp increase in water head	No change in the water head	A sharp decrease in water head	Uncertain water head behavior	-
	Section 4	Uncertain seepage behavior	Uncertain seepage behavior	Uncertain seepage behavior	Uncertain seepage behavior	-
		A sharp increase in water head	Quite slight changes and no change in seepage	A sharp decrease in water head	Uncertain water head behavior	-
	Section 5	Uncertain seepage behavior	Uncertain seepage behavior	Uncertain seepage behavior	Uncertain seepage behavior	-
		Quite a slight increase and no change in the water head	No change in the water head	A quite slight decrease in water head	Decrease in water head	-
Toe Fiter	Section 1	Slight decrease in seepage	No change in seepage	Slight increase in seepage	-	Slight changes in seepage
		A sharp increase in water head	No change in the water head	No change in the water head	-	No change in the water head
	Section 2	A sharp increase in seepage 100 m reservoir level	Quite slight changes and no change in seepage	Slight changes in seepage	-	Slight changes in seepage

[1] For the Chimney filter take as increase in the height of the filter

		A sharp increase in water head	No change in the water head	Slight decrease in water head	-	Quite slight changes and no change in the water head
	Section 3	Uncertain seepage behavior	Uncertain seepage behavior	Slight changes in seepage	-	Slight changes in seepage
		A sharp increase in water head	No change in the water head	A sharp decrease in water head	-	Quite slight changes and no change in the water head
	Section 4	Uncertain seepage behavior	Uncertain seepage behavior	Uncertain seepage behavior	-	Uncertain seepage behavior
		A sharp increase in water head	Quite slight changes and no change in the water head	Uncertain water head behavior	-	Uncertain water head behavior
	Section 5	Uncertain seepage behavior	Slight increase in seepage	Uncertain seepage behavior	-	Uncertain seepage behavior
		Uncertain water head behavior	Uncertain water head behavior	Uncertain water head behavior	-	A sharp decrease in water head
Chimney Filter	**Section 1**	Slight decrease in seepage	Quite a slight increase and no change in seepage	Uncertain seepage behavior	Uncertain seepage behavior	-
		A sharp increase in water head	No change in the water head	No change in the water head	No change in the water head	-
	Section 2	A sharp increase in seepage 100 m reservoir level	Quite a slight increase and no change in the water head	Uncertain seepage behavior	Uncertain seepage behavior	-
		A sharp increase in water head	No change in the water head	Increase and no change in water head	Slight increase and no change in the water head	-
	Section 3	Uncertain seepage behavior	Uncertain seepage behavior	Uncertain seepage behavior	Uncertain seepage behavior	-
		Uncertain water head behavior	Uncertain water head behavior	A sharp increase in water head	Uncertain water head behavior	-
	Section 4	Uncertain seepage behavior	Uncertain seepage behavior	Uncertain seepage behavior	Uncertain seepage behavior	-
		Uncertain water head behavior	Uncertain water head behavior	Uncertain water head behavior	Uncertain water head behavior	-
	Section 5	Uncertain seepage behavior	Uncertain seepage behavior	Uncertain seepage behavior	Uncertain seepage behavior	-
		No change in the water head	No change in the water head	No change in the water head	Increase in water head	-

CHAPTER 5
CONCLUSION

Embankment dams are widely used due to their easy construction using materials available nearby. However, seepage is a major concern that can cause dam failure, and it is impossible to prevent seepage without a completely impermeable structural element. Nevertheless, preventive or control methods like relief wells and trench drains can help avoid problems caused by seepage. Drain filters, such as toe drains and protective filters like chimney and blanket filters, are used in dams to prevent water flow and facilitate drainage between layers.

Seepage anomalies can often cause visible effects such as wet areas and settlements in the dam body. However, at times, they may occur in a location that remains unnoticed. Hence, various seepage instrumentation and calculation methods have been developed to address this issue. These seepage calculation methods are used to evaluate the impact of seepage on a dam and to locate probable seepage pathways. In this study, the Finite Element Method formed the basis of the analyses. Two FEM-based software were utilized due to their advantages. The PLAXIS 2D software was used to examine the reliability of the design of a homogeneous dam, which will serve as the basis for 273 different dams. The study analyzed a total of 273 dams for seepage, and using SEEP/W, determined the seepage and water head in five different sections of the dams.

The seepage and maximum water head in the sections for five different sections of the 273 embankment dams modelled were examined. The analysis was based on three filter types used in the dams: blanket, toe, and chimney. Each filter type was examined in terms of the variable accepted feature. These features include the reservoir water head, permeability of filter material, length of the filter, thickness of the filter, and slope of the filter. The study compared different filter types with each other to understand which is the most ideal design and which filters cause unsuccessful results.

- It has been observed that the seepage in the first two sections of dams with blanket filters increases with an increase in the reservoir level. However, there are variations in the remaining sections depending on the design of the dam, and a general behavior pattern can not be determined. Similarly, the change in the seepage in dams with toe filters is similar to dams with blanket filters for the first two sections. While the change in subsequent sections in dams with toe filters is too variable to reach a general conclusion as in dams with blanket filters, the fluctuations in seepages are not as sharp as in blankets. In chimney filter dams, the situation is similar to that of dams with blanket and toe filters for the first two sections and the seepage increases. However, the seepage behavior in the next section of chimney filter dams is unpredictable, like toe and blanket filter dams, and requires analysis specific to each dam.

- In the first four sections of dams with blanket and toe filters, the water head in the sections increases in parallel with the increase in the reservoir water head. In dams with blanket filters, the water head in the final section increases in some dams and remains constant in others. In dams with toe filters, it is not possible to make a general conclusion about the change in water head in the final section. While in the first two sections of dams with chimney filters, an increase in water head in a section is observed parallel to the increase in reservoir level, the behavior in the third and fourth sections can not be generalized and requires a dam-specific investigation. In the last section of the chimney filter dam, there is no significant change in the section water head.
- When examining the impact of the permeability of filter material on the seepage in dams with different filter types, it has been observed that the initial section of all dams with blanket, toe, and chimney filters exhibit almost no change in the seepage. In the second section, small variations in seepage are present across all dams, but these changes are not a linear increase or decrease. In the third section, lower seepage changes are observed in dams with blanket and toe filters in comparison to those with chimney filters. Sharp seepage increases and decreases are observed in chimney dams. As the final section of the dam is approached, the seepage in dams with toe filters decreases steadily for almost all dams. While dams with blanket filters exhibit sharp movements, a regular pattern can not be detected. Although most dams with chimney filters experience regular decreases in seepage, the number of dams with exceptionally different behavior should not be underestimated.

- Upon analyzing the impact of the reduction in filter permeability on the water head in different sections, it was found that the effect is not significant across all filter types. In all but a few exceptional cases, the change in permeability does not have a considerable impact on the water head in the remaining three sections of dams with blanket filters. On the other hand, for dams with toe filters, there is a noticeable but irregular increase and decrease in the section water head in some dams, particularly in the last two sections. In chimney filter dams, the increases and decreases are more prominent and are observed in more varied dam designs in the third and fourth sections. However, in the last section of dams with chimney filters, the water head remains almost unchanged, indicating that the section water head is at the same level in all dams.
- In the context of this research, physical properties analysis was conducted for the components of blanket filter, toe filter, and chimney filter. It is worth noting that the results of this analysis will be presented without comparison between each other. This is because the effect of thickness and length were examined for the blanket, while the slope and length were analyzed for the toe filter. Furthermore, the change in thickness and height parameters were discussed exclusively for the chimney. Such an approach ensures that each component is examined in a thorough and detailed manner, and allows for a comprehensive understanding of the unique physical characteristics of each element.
- The analysis of the graphs reveals that the length of the blanket influences the maximum seepage in dam sections, with varying degrees of impact in sections where the blanket filter is located. However, this relationship is non-linear, and the effects of blanket length must be examined on a case-by-case basis. Specifically, an increase in blanket length does not affect the water head in the upstream part of the dam, but it significantly decreases towards the center of the dam. Finally, there is a slight decrease in the downstream region.
- Increasing the thickness of the blanket filter impacts seepage in a dam. The effect is more pronounced downstream and varies between varied dam designs. The change in blanket filter thickness does not seem to have a clear effect on the water head in the first two sections. However, it causes sharp changes for some varied dam designs in the next two sections, but not all dams behave this

way. In the last section, the water head in all dams without exception increases as the thickness increases.

- The study's findings show that dams with a homogeneous toe filter are sensitive to changes in the slope of the filter. While the impact on seepage is minor in the first few sections of the dam, it becomes more significant in the later sections. In the first two sections, the water head is not affected much, and in the third section, there are only small changes. However, in the fourth section, even minor changes in the angle of the toe filter can cause noticeable increases or decreases in the water head. If the toe filter is steeper, the water head in the last section of the dam will be lower.
- Increasing the horizontal length of the toe filter in dams generally leads to minor changes in seepage. However, the outcomes of these changes vary depending on the design of the dam, making it difficult to determine a general pattern of behavior. Similarly, the effect on the water head in different sections of the dam also varies depending on the design of the dam. While the impact on the water head in the first section is not very noticeable, it becomes more apparent in the second section. The water head decreases for all dams in the third section, but the behavior of the water head in the last two sections is more diverse and irregular.
- In dams with chimney filters, it is observed that the seepage is affected only slightly by changes in filter thickness for the first two sections, while sharp increases and decreases are observed in the next three sections. A general pattern for this seepage behavior can not be drawn. Similarly, in many other dam analyses, the change in head due to a change in filter thickness is minimal for the first two sections. However, the change in the head in the third and fourth sections is sharper and more variable, depending on the design of the dam. Finally, in the last section, it is observed that the thickness and head almost reach the same level for all dams.
- Finally, the study investigated the impact of chimney height on seepage and water head on a dam body. Results showed that there were slight changes in the first two sections and more significant changes in the last three sections in terms of seepage. However, the changes were not consistent across different dams, and there was no regular behavior parallel to the increase in chimney

height. The study suggests that increasing the chimney height generally increases from the water head, but the impact varies across different sections. In the second section, there was an increase in water head in some dams, while in the third and fourth sections, a few exceptions were observed. In the last section, no effect was observed, meaning that the water head remained constant in all dams.

The findings of the study suggest that it is inappropriate to generalize the analysis of the variation of seepage and water head behavior in the dam body with multiple parameters in filter dams and to assert that all varied dam designs exhibit similar behavior. Notably, the dam section closest to the reservoir displayed the least effect of the change in almost all parameters. Additionally, distinct effects were observed for each changing parameter in all sections, and no behavioral pattern could be established. The study reveals that the seepage behavior of nearly every dam design is unique to the dam itself. Therefore, it is imperative to conduct a specific analysis for each dam, identify the underlying reasons for the seepage behavior, and establish design principles accordingly.

REFERENCES

Abhilasha, P. S., and Balan, A. (2014). Numerical Analysis of Seepage in Embankment Dams. *IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)*, 1323.

Aboelela, M. M. (2016). Control of Seepage through Earth Dams Based on Pervious Foundation Using Toe Drainage Systems. *Journal of Water Resource and Protection*, *8*(12), 1158–1174.

Alateya, H., and Asr, A. (2018). *Numerical analysis of the influence of cavities on seepage through earth dams*.

AlJairry, H. H. (2010). 2D Flow Analysis through Zoned Earth Dam Using Finite Element Approach. *Eng. and Tech. Journal*, *28*(21).

Arshad, I., and Babar, M. M. (2014). Comparison of SEEP/W Simulations with Field Observations for Seepage Analysis through an Earthen Dam (Case Study: Hub Dam – Pakistan). *International Journal of Research*.

Arulanandan, K., and Perry, E. B. (1983). Erosion in Relation to Filter Design Criteria in Earth Dams. *Journal of Geotechnical Engineering*, *109*(5), 682–698.

Baozhong, Z. (1981). Seepage calculation of earth dam with impervious blanket and inclined wall on infinite deep permeable foundation. *J. Hydraul. Eng.*, *5*, 61–68.

Bardet, J. P., and Tobita, T. (2002). A practical method for solving free-surface seepage problems. *Computers and Geotechnics*, *29*(6), 451–475.

Batelaan, O., and De Smedt, F. (2004). SEEPAGE, a New MODFLOW DRAIN Package. *Groundwater*, *42*(4), 576–588.

Bayat, M., Eslamian, S., Shams, G., and Hajiannia, A. (2019). The 3D analysis and estimation of transient seepage in earth dams through PLAXIS 3D software: neural network. *Environmental Earth Sciences*, *78*(18).

Bear, J. (1792). *Dynamics of Fluids in Porous Media*. American Elsevier Publishing Company.

Beer, G., and Duenser, C. (2019). Isogeometric boundary element analysis of problems in potential flow. *Computer Methods in Applied Mechanics and Engineering*, *347*, 517–532.

Benmebarek, N., Benmebarek, S., and Kastner, R. (2005). Numerical studies of seepage failure of sand within a cofferdam. *Computers and Geotechnics*, *32*(4), 264–273.

Bennett, P. T. (1946). The Effect of Blankets on Seepage through Pervious Foundations. *Transactions of the American Society of Civil Engineers*, *111*(1), 215–228.

BENTLEY.. *PLAXIS 2D: Geotechnical Engineering Software | Bentley Systems*. https://www.bentley.com/software/plaxis-2d/ (2023, March 10)

Brown, J. G., and Jackson, D. C. *Dam | Definition, History, Types, Environmental Impacts, Examples, and Uses | Britannica*. https://www.britannica.com/technology/dam-engineering (2023, January 28).

Budhu, M. (2007). *Soil mechanics and foundations*. Wiley India.

Calamak, M., Yanmaz, A. M., and Kentel, E. (2017). Probabilistic Evaluation of the Effects of Uncertainty in Transient Seepage Parameters. *Journal of Geotechnical and Geoenvironmental Engineering*, *143*(9), 06017009.

Calamak, M., Yilmaz, A. N., and Yanmaz, A. M. (2018). Performance Evaluation of Internal Drains of Earthen Dams. *Journal of Performance of Constructed Facilities*, *32*(6), 04018085.

Chang, C. S. (1988). BoundaryElement Analysis for Unconfined Seepage Problems. *Journal of Geotechnical Engineering*, *114*(5), 556–572.

Changxi, M. (1963). Computation of seepage through earth dams with upstream blanket and sloping core. *J. Hydraul. Eng.*, *1*, 26–43.

Sari, U., Prabandiyani Retno Wardani, S., Suharyanto, and Partono, W. (2017). Influence of pore water pressure to seepage and stability of embankment dam (case study of Sermo Dam Yogyakarta, Indonesia). *MATEC Web of Conferences*, *101*.

Cedergren, H. R. (1977). *Seepage, Drainage, and Flow Nets*. Wiley.

Deng, G., Cao, K., Chen, R., Zhang, X., Yin, Q., and Zhou, H. (2018). A simple approach to evaluating seepage through thin impervious element of high embankment dams. *Environmental Earth Sciences*, *77*(1), 1–11.

Dupuit, J. (1963). *Études théoriques et pratiques sur le mouvement des eaux dans les canaux*.

FEMA. (2011). *Filters for Embankment Dams: Best Practices for Design and Construction* (FEMA, Ed.). Federal Emergency Management Agency.

Foster, M., Fell, R., and Spannagle, M. (2000). The statistics of embankment dam failures and accidents. *Canadian Geotechnical Journal*, *37*(5), 1000–1024.

Gan, J. K., and Mc Donald, L. A. (1999). Mardi Dam A Case Study on Permeable Structures. *International Symposium on Dam Foundations: Problems and Solutions*.

Geostudio. "Products/SEEP W" https://www.geoslope.com/products/seep-w (2023, January 15)

Harr, M. E. (1962). *Groundwater and Seepage*.

Hartono, S. (2002). Prediction of transient head on seepage path using Boundary Fitted Coordinate (BFC) system. *LSU Master's Theses*.

Higginbottom, J. (2019). *Dam collapse that China kept secret | MCLC Resource Center*.

Hussain, I. A. A., Kashyap, D., and Prasad, K. S. H. (2007). Seepage Modeling Assisted Optimal Design of a Homogeneous Earth Dam: Procedure Evolution. *Journal of Irrigation and Drainage Engineering*, *133*(2), 116–130.

Hutchison, W. R. (1983). *Earth Dam Seepage Analysis with a Programmable Calculator*.

ICODS. (2015). *Evaluation and Monitoring of Seepage and Internal Erosion* . FEMA.

ICOLD. "ICOLD CIGB > General Synthesis." https://www.icold-cigb.org/GB/world_register/general_synthesis.asp (2023, January 19)

Indraratna, B., and Raut, A. K. (2006). Enhanced Criterion for Base Soil Retention in Embankment Dam Filters. *Journal of Geotechnical and Geoenvironmental Engineering*, *132*(12), 1621–1627.

Irzooki, H. (2016). Computation of Seepage through Homogenous Earth Dams with Horizontal Toe Drain . *Engineering and Technology Journal*, *34*, 430–440.

Jamel, A. A. J. (2018). Investigation and Estimation of Seepage Discharge Through Homogenous Earth Dam with Core by Using SEEP/W Model and Artificial Neural Network. *Diyala Journal of Engineering Sciences*, *11*(3), 54–61.

Jassam, M. G., and Abdulrazzaq, S. S. (2019). Theoretical Analysis of Seepage through Homogeneous and Non-homogeneous Saturated-Unsaturated Soil. *Journal of Engineering*, *25*(5), 52–67.

Kacimov, A. R., Al-Maktoumi, A., and Obnosov, Y. V. (2019). Seepage through earth dam with clay core and toe drain: the Casagrande–Numerov analytical legacy revisited. *27*(S1), 264–272.

Kamaratih, D., Widodo, N. P., Senjaya, T., and Wattimena, R. K. (2022). Experimental and Analytical Study of The Water Phreatic Level on The Stability of Laboratory Scale Dam Using Slide2 Software. *International Symposium on Earth Science and Technology*.

Kassif, G., Komornik, A., Wiseman, G., Zeitlen, J.G. (1965). Studies and design criteria for structures on expansive clays. *Proc. 1st Res. Conf. on Exp. Soils, Texas*

Kermani, E. F., and Barani, G. A. (2012). Seepage Analysis through Earth Dam Based on Finite Difference Method. *Journal Of Basic and Applied Scientific Research 2*, *11*, 11621–11625.

Khalid, S., Singh, B., Nayak, G. C., and Jain, O. P. (1990). Nonlinear analysis of concrete face rockfill dam. *Journal of Geotechnical Engineering*, *116*(5), 822–837.

Khazaei, J., and Asadi, M. (2014). Seepage analysis in body and foundation of Dam using the Seep/3D and Seep/W Braced excavations View project Soil-Foundation-Structure Interaction View project *Journal of Science and Today's World*. *3*, 457–461.

Kirra, M. S., Shahien, M., Elshemy, M., and Zeidan, B. (2015). Seepage and Slope Stability Analysis of Mandali Earth Dam, Iraq: A Case Study. *International Conference on Advances in Structural AndhemGeotechnical Engineering, ICASGE15*.

Kumar, S., Sahu, A. K., and Kumar, M. (2022). Modelling the effect of the central impervious core and downstream filter geometry on seepage through earth dams. *Ain Shams Engineering Journal*, *13*(1), 101510.

Li, G. C., and Desai, C. S. (1983). Stress and Seepage Analysis of Earth Dams. *Journal of Geotechnical Engineering*, *109*(7), 946–960.

Liggett, J. A. (1977). Location of Free Surface in Porous Media. *Journal of the Hydraulics Division*, *103*(4), 353–365.

Li, G., Shen, Z., and Yang, C. (2020). A Simplified Calculation Method of Seepage Flux for Slope-Wall Rock-Fill Dams with a Horizontal Blanket. *Applied Sciences 2020, Vol. 10, Page 3848*, *10*(11), 3848.

Li, H., Zhao, F., and Li, J. (2019). Seepage analysis of clay core wall dam based on ABAQUS. *IOP Conference Series: Earth and Environmental Science*, *384*(1), 012015.

Lindeburg, M. R. (1986). *Civil Engineering Reference Manual for the PE Exam* (Fifteenth Edition). Professional Publications.

Li, Y., Rahardjo, H., and Irvine, K. N. (2018). Seepage and deformation analyses in unsaturated soils using ansys. *Springer Series in Geomechanics and Geoengineering*, 360–364.

Lü, C., Li, Z., and Li, D. (2018). Problems of Applying Seepage Pressure in Coupling Analysis of Seepage and Stress Using ABAQUS. *Journal Od Yangtze River Scientific Research Instı*, *35(5)*, 68–72.

Mansuri, B., and Salmasi, F. (2013). Effect of Horizontal Drain Length and Cutoff Wall on Seepage and Uplift Pressure in Heterogeneous Earth Dam with Numerical Simulation.

Ma, S. Q., Cai, S. J., and Guo, M. (2012). Seepage-stability analysis of a mine tailings dam in Yunnan province based on ANSYS. *Applied Mechanics and Materials*, *226–228*, 1406–1410.

Mavroulidou, M. (1999). *Numerical Modelling of Seepage in the Presence of Phreatic Surfaces*.

Mishra, G. C., and Parida, B. P. (2006). Earth Dam with Toe Drain on an Impervious Base. *International Journal of Geomechanics*, *6*(6), 379–388.

Moayed, R. Z., Rashidian, V., and Izadi, E. (2012). Evaluation of phreatic Line in Homogeneous Earth Dams With Different Drainage System. *32. nd Annual USSD Conference on Innovative Dam and Levee Design and Construction for Sustainable Water Management*.

Moayeri, M. S. (1972). Seepage through Dams with Horizontal Toe Drain. *Journal of the Soil Mechanics and Foundations Division*, *98*(5), 461–479.

Moharrami, A., Hassanzadeh, Y., Salmasi, F., Moradi, G., and Moharrami, G. (2014). Performance of the horizontal drains in upstream shell of earth dams on the upstream slope stability during rapid drawdown conditions. *Arabian Journal of Geosciences*, *7*(5), 1957–1964.

Mukhopadhyay, S. (2008). Seepage Analysis through Foundation using F.E.M. and Flownet. *The 12th International Conference of International Association for Computer Methods and Advances in Geomechanics (IACMAG)*, 4175–4182.

Neuman, S. P., and Witherspoon, P. A. (1970). Finite Element Method of Analyzing Steady Seepage with a Free Surface. *Water Resources Research*, *6*(3), 889–897.

Özer, A. T., and Bromwell, L. G. (2012). Stability assessment of an earth dam on silt/clay tailings foundation: A case study. *Engineering Geology*, *151*, 89–99.

Patel, V. J., Krishnayya, A. V. G., and Arora, K. L. (1964). Mechanics of Inclined Filters in Earth Dams. *Journal of the Soil Mechanics and Foundations Division*, *90*(2), 87–110.

Polubarinova-Kochina. (1962). *Theory of Ground Water Movement*. Princeton University Press.

Refaiy, A. R., AboulAtta, N. M., Saad, N. Y., and El-Molla, D. A. (2021). Modeling the effect of downstream drain geometry on seepage through earth dams. *Ain Shams Engineering Journal*, *12*(3), 2511–2531.

Remson, Irwin., Hornberger, G. M., and Molz, F. J. (1971). *Numerical methods in subsurface hydrology, with an introduction to the finite element method*. 389.

Rezk, M. A. E. R. M., and Abo Elela, M. M. (2015). Minimum height of the trapezoidal filter in earth dams using Complex Function Theory. *Alexandria Engineering Journal*, *54*(4), 1219–1224.

Rezk, M. A. E. R. M., and Senoon, A. A. A. A. (2012). Analytical solution of earth dam with upstream blanket. *Alexandria Engineering Journal*, *51*(1), 45–51.

Rezk, M. A. E. R. M., and Senoon, A. E. A. A. A. (2011). Analytical solution of seepage through earth dam with an internal core. *Alexandria Engineering Journal*, *50*(1), 111–115.

Rushton, K. R., and Redshaw, S. C. (1979). Seepage and Groundwater Flow. *Earth Surfaces*, *5*, 339.

Salem, M. N., Eldeeb, H. M., and Nofal, S. A. (2019). Analysis of Seepage through Earth Dams with Internal Core. *International Journal of Engineering Research and Technology*, *8*(8).

Sharma, R., and Manna, B. (2021). Failure Analysis of Homogeneous Earthen Dam. *Lecture Notes in Civil Engineering*, *138*, 829–837.

Sheikh Suleimany, J. M., and Mamand, B. S. (2020). Estimating Seepage Quantity through Homogenous Earth-Fill Dam with Horizontal Drainage Using Different Methods. *Zanco Journal of Pure and Applied Sciences*, *32*(1), 7–18.

Smith, N. (1972). *A History of Dams* (First American). Citadel Press.

Soleymani, S., and Akhtarpur, A. (2011). *Seepage Analysis for Shurijeh Reservoir Dam Using Finite Element Method*. 3227–3234.

Stephens, T. (2010). Manual on Small Earth Dams: A Guide to Siting, Design, and Construction. *FAO Drainage and Irrigation Paper, Number 64*, 114.

The Editors of Encyclopaedia Britannica. "*Typhoon Nina–Banqiao dam failure | Chinese history [1975] | Britannica*." https://www.britannica.com/event/Typhoon-Nina-Banqiao-dam-failure (2023, March 23)

The Editors of Encyclopaedia Britannica. "*La rotura del pantano de Puentes - Región de Murcia Digital*." https://www.regmurcia.com/servlet/s.Sl?sit=c,373,m,1096andr=ReP-16664-DETALLE_REPORTAJES (2023, February 8)

Thieu, N. T. M., Fredlund, D. G., and Hung, V. Q. (2000). General partial differential equation solvers for saturated-unsaturated seepage. In *Unsaturated Soils for Asia* (pp. 201–206). CRC Press.

Uginchus, A. A. (1966). *Seepage Through Earth Dams: (Raschet Fil'tratsii Cherez Zemlyanye Plotiny)*. Israel Program for Scientific Translations.

USBR. (1987). *Design of small dams*.

USSD. (2011) 21st Century Dam Design. *Annual USSD Conference*.11-15

USSD. *Materials for Embankment Dams* (U. S. Society on Da…). www.ussdams.org (2023, March 9)

USACE. (1941). *Investigation of filter requirements for underdrains.*

USACE. (1942). *Field and laboratory investigation of design criteria and drainage wells.*

USACE. (1953). *Filter Experiments and Design Criteria:Techical Momerandum No. 3-360.*

USACE. (2004). General Design and Construction Considerations for Earth and Rock-Fill Dams. In *Engineer manual: Vol. EM 1110-2-*. University Press of the Pacific.

USACE. (1986). *Seepage Analysis and Control for Dams-Engineer Manual No. 1110-2-1901*.

USBR. (1947). *Laboratory Tests on Protective Filters for Hydraulic and Static Structures*.

USBR. (1955). *The Use of Laboratory Tests to Develop Design Criteria for Protective Filters*.

NRSC (1979). *Soil Mechanics Note No. 7 The Mechanics of Seepage Analyses*.

USBR. (1990). *Earth Manual Part II* (USBR, Ed.; Third Edition). United States Government Printing Office.

USBR. (2012). *Design Standards No:13, Chapters 2: Embankment Design,* 2–5.

Vaughan, P. R., and Soares, H. F. (1982). Design of Filters for Clay Cores of Dams. *Journal of the Geotechnical Engineering Division*, *108*(1), 17–31.

Vick, S. G. (1983). *Planning, design, and analysis of tailings dams.*

Wright, D. E. (1990). *Training Aids for Dam Safety: Module Evaluation of Seepage Conditions*. Breu of Reclamation.

Xu, C. (2019). *Long-Term Seepage Assessment Using Numerical Modeling for Upstream-Type Tailings Dams*. Concordia University.

Yanmaz, A. Melih. (2001). *Applied Water Resources Engineering*. 470.

Yarahmadi, N., Khodashenas, S. R., and Ansari, S. (2014). A comparison between two and three dimensional seepage analysis results in earth dams using SEEP/W and SEEP/3D (Case study: Shian and Khaan-Abad Dams). *Ecology, Environment and Conservation*, *21*.

Yoshitake, Y., Kobayashi, N., Fujihara, M., and Nishiyama, T. (2012). An Analytical Solution of Seepage Discharge from a Reservoir of Embankment Dam with Triangular Soil Blanket and its Applicability. *TJSID*, *79*(2), 109–115.

Yüce M. İ. and Yüce S. (2016). Pre-feasibility Assessment of Small Hydropower Projects in Turkey by RETScreen. *Journal American Water Works Association*, 108(5), E269-E275.

Zedan, A. J., Faris, M. R., and Abdulsattar, A. A. (2018). Slope stability of an Earth Dam during drawdown conditions (KHASA-CHAI Dam) as a case study. *International Journal of Engineering and Technology(UAE)*, *7*(4), 17–21.

Zeidan, A. "*Ma'rib | Yemen, Dam, God, and History | Britannica*." Britannica. https://www.britannica.com/place/Marib (2023, January 15)

Zewdu, A., Zewdu Belew, A., Yigezu Tenagashaw, D., Tadesse Ayele, W., and Gebrie, T. (2021). *Modelling of Seepage and Slope Stability Analysis of Ribb Embankment Dam, Ethiopia*.

Zhongru, W., Huanxiang, R., and Dasong, C. (2002). *Dam Safety Monitoring Theory and Its Application* . China Education Press.

APPENDIX

Table A.1. Results for Blanket Filter

Code	Seepage in 100m	Seepage in 200m	Seepage in 300m	Seepage in 400m	Seepage in 500m	Head in 100m	Head in 200m	Head in 300m	Head in 400m	Head in 500m
B101	8,8375E-07	2,8459E-19	3,91E-19	1,86E-20	5,04E-47	50	42,5472	32,199	17,3773	0,537
B102	4,3122E-07	4,5064E-19	4,44E-19	2,61E-19	3,07E-17	75	71,3318	54,494	28,9249	0,5644
B103	3,0042E-07	2,8205E-06	4,95E-19	2,88E-19	2,54E-45	100	100	81,085	44,1077	0,6246
B104	8,8115E-07	6,729E-20	1,22E-19	1,02E-19	2,51E-44	50	42,5723	33,072	17,5823	1,0403
B105	4,3085E-07	2,4729E-19	7,96E-19	1,68E-19	1,41E-18	75	71,3344	54,457	28,9729	1,0544
B106	3,0098E-07	2,8256E-06	6,34E-19	1,91E-19	1,41E-18	100	100	81,074	45,2014	1,1018
B107	8,8089E-07	2,6765E-19	2,3E-19	5,93E-20	2,28E-46	50	42,576	33,088	17,6317	2,018
B108	4,3333E-07	1,2193E-18	4,4E-19	2,73E-19	2,14E-45	75	71,3139	54,434	28,7422	2,0335
B109	3,0163E-07	2,8316E-06	1,09E-18	2,03E-19	1,56E-17	100	100	80,972	44,3186	2,0628
B110	8,8017E-07	1,5924E-19	3,37E-19	1,24E-19	4,12E-19	50	42,577	33,084	17,4712	0,5375
B111	4,3074E-07	3,2524E-19	4,3E-19	3,49E-19	2,71E-17	75	71,3358	54,516	28,961	0,565
B112	3,0039E-07	2,8202E-06	4,29E-19	2,54E-19	-8,77E-49	100	100	81,087	44,2396	0,6313
B113	8,8114E-07	2,3621E-19	1,25E-19	2,17E-19	1,82E-44	50	42,5723	33,072	17,5825	1,0403
B114	4,3284E-07	4,9973E-19	6,47E-19	1,88E-19	1,05E-47	75	71,3174	54,363	28,7368	1,0525
B115	3,0046E-07	2,8208E-06	7,62E-19	1,9E-19	2,99E-44	100	100	81,114	44,5239	1,1116
B116	8,809E-07	1,965E-19	2,1E-19	1,73E-19	7,05E-20	50	42,576	33,088	17,6245	2,0179
B117	4,3191E-07	1,2328E-18	6E-19	6,23E-20	3,52E-19	75	71,326	54,5	28,743	2,0347
B118	3,0151E-07	2,8305E-06	7,76E-19	2,1E-19	2,11E-19	100	100	81,012	44,5194	2,064
B119	8,8353E-07	2,6426E-19	1,76E-19	3,39E-20	1,16E-47	50	42,5489	33,017	17,3721	0,5368
B120	4,3179E-07	4,7764E-19	3,15E-19	1,71E-19	5,48E-17	75	71,327	54,468	28,8775	0,5671
B121	3,0003E-07	2,817E-06	4,13E-19	3,2E-19	1,36E-20	100	100	81,069	46,8137	0,6275

B122	8,811E-07	3,0762E-19	1,32E-19	1,35E-19	1,36E-20	50	42,5726	33,073	17,5822	1,0403
B123	4,3163E-07	3,9132E-19	7,42E-19	2,8E-19	2,56E-21	75	71,3276	54,42	28,858	1,0532
B124	3,0068E-07	2,8228E-06	6,78E-19	1,61E-19	2,56E-21	100	100	81,088	44,2863	1,1108
B125	8,8077E-07	2,8629E-19	2,9E-19	1,35E-20	5,23E-48	50	42,5764	33,091	17,6353	2,0178
B126	4,3245E-07	9,4864E-19	4,24E-19	3,68E-19	6,78E-20	75	71,3207	54,487	28,7729	2,0336
B127	3,0153E-07	2,8307E-06	9,44E-19	2,21E-19	2,71E-20	100	100	81,009	44,5133	2,0617
B128	1,0438E-06	1,6601E-19	2,02E-19	3,73E-13	3,96E-18	50	41,1354	28,622	8,06241	0,5082
B129	5,3826E-07	5,4882E-19	2,2E-19	5,9E-13	5,2E-18	75	70,4168	48,836	14,0053	0,5149
B130	3,9969E-07	3,7234E-06	3,14E-19	3,47E-18	9,45E-46	100	100	76,629	22,9381	0,5365
B131	1,0478E-06	1,8295E-19	2,35E-19	3,63E-15	3,47E-18	50	41,0289	28,606	8,25301	1,0066
B132	5,3963E-07	3,9639E-19	2,57E-19	6,02E-15	1,73E-18	75	70,4034	48,697	14,1403	1,0121
B133	4,0019E-07	3,7282E-06	4,68E-19	2,62E-44	1,73E-18	100	100	76,616	23,8116	1,0218
B134	1,0478E-06	1,8634E-19	1,73E-19	8,67E-18	9,58E-11	50	41,1418	28,708	9,00604	2,0046
B135	5,3999E-07	3,7267E-19	6,05E-19	1,73E-18	8,67E-19	75	70,4002	48,72	14,228	2,0072
B136	4,0124E-07	3,7375E-06	9,57E-19	7,13E-13	5,2E-18	100	100	76,694	23,7836	2,0138
B137	1,0438E-06	1,8295E-19	1,98E-19	3,71E-13	2,62E-19	50	41,1352	28,622	8,06282	0,5082
B138	5,3852E-07	4,2685E-19	1,9E-19	5,87E-13	8,99E-46	75	70,4143	48,826	14,0187	0,5148
B139	3,9949E-07	3,7217E-06	3,16E-19	4,34E-19	1,12E-47	100	100	76,651	23,0844	0,5366
B140	1,0477E-06	1,9989E-19	2,15E-19	3,6E-15	2,17E-19	50	41,0263	28,61	8,25567	1,0066
B141	5,4097E-07	4,8618E-19	4,13E-19	5,93E-15	5,42E-19	75	70,3936	48,623	13,9279	1,0117
B142	3,9945E-07	3,7218E-06	3,22E-19	5,42E-19	1,05E-44	100	100	76,629	23,0878	1,0209
B143	1,046E-06	2,6088E-19	1,02E-19	6,81E-45	9,58E-12	50	41,1417	28,709	9,00076	2,0046
B144	5,3964E-07	4,5398E-19	2,66E-19	8,67E-19	3,29E-19	75	70,4029	48,739	14,2606	2,0072
B145	4,008E-07	3,7329E-06	5,09E-19	9,76E-19	4,17E-47	100	100	76,707	23,5737	2,0138
B146	1,043E-06	3,117E-19	3,22E-19	3,56E-13	5,8E-20	50	41,1424	28,632	8,03835	0,5074
B147	5,3812E-07	4,2686E-19	9,82E-20	5,51E-13	4,61E-20	75	70,4178	48,844	13,9451	0,5147

B148	3,9926E-07	3,7197E-06	3,73E-19	2,71E-20	2,04E-47	100	100	76,666	23,0472	0,5366
B149	1,0478E-06	2,2022E-19	1,68E-19	3,34E-15	1,36E-20	50	41,0283	28,611	8,26208	1,0066
B150	5,3743E-07	2,9345E-19	2,41E-19	5,72E-15	1,37E-47	75	70,4234	48,796	14,2458	1,0122
B151	3,998E-07	3,7239E-06	9,11E-19	6,63E-47	3,39E-45	100	100	76,605	23,3937	1,0213
B152	1,046E-06	3,4897E-19	2,17E-19	1,07E-47	9,58E-12	50	41,1417	28,709	9,00076	2,0046
B153	5,3965E-07	4,9315E-19	4,93E-19	6,78E-20	6,78E-21	75	70,4031	48,743	14,2569	2,0072
B154	4,0079E-07	3,733E-06	8,89E-19	4,07E-20	3,39E-20	100	100	76,741	23,5512	2,0138
B155	1,2861E-06	1,4907E-19	6,44E-20	1,4E-47	6,43E-48	50	38,7515	21,787	3,44945	0,5038
B156	7,0912E-06	4,8511E-18	1,92E-18	2,79E-18	1,73E-18	75	69,2104	39,556	5,93672	0,5055
B157	5,809E-07	5,3109E-06	2,85E-19	1,73E-18	3,88E-46	100	100	68,564	10,0628	0,5105
B158	1,3191E-06	1,6432E-19	1,51E-19	5,2E-18	2,88E-18	50	38,7059	21,728	3,81191	1,0024
B159	7,117E-07	6,8073E-19	2,3E-19	4,88E-18	2,88E-18	75	69,1733	39,495	6,25589	1,0044
B160	4,0019E-07	3,728E-06	8,27E-19	9,24E-15	3,47E-18	100	100	76,62	23,2941	1,0204
B161	1,2926E-06	1,6432E-19	1,56E-19	8,77E-11	5,2E-18	50	38,6928	21,925	4,58514	2,0023
B162	7,1363E-07	2,8457E-19	1,59E-19	2,29E-18	3,89E-18	75	69,1417	39,554	6,88101	2,0026
B163	5,8585E-07	5,3538E-06	2,98E-19	1,73E-18	3,78E-45	100	100	68,428	10,9821	2,0049
B164	1,2992E-06	2,3377E-19	1,27E-19	2,59E-48	6,55E-45	50	38,6355	21,621	3,41919	0,5038
B165	7,119E-06	3,4421E-18	2,47E-18	1,63E-45	2,17E-19	75	69,0295	39,54	5,91821	0,5055
B166	5,8094E-07	5,3112E-06	2,78E-19	6,5E-19	2,49E-45	100	100	68,621	10,1909	0,5106
B167	1,3191E-06	4,8618E-19	1,47E-19	2,17E-19	4,34E-19	50	38,7061	21,727	3,81174	1,0024
B168	7,1334E-07	4,6408E-19	2,02E-19	2,27E-19	4,34E-19	75	68,8141	39,541	6,29222	1,0045
B169	3,9967E-07	3,7233E-06	6,1E-19	9,22E-15	2,17E-19	100	100	76,632	23,3411	1,0202
B170	1,2921E-06	1,7279E-19	1,05E-19	8,77E-12	UNKNOWN	50	38,6975	21,932	4,58572	2,0023
B171	7,1366E-07	2,1005E-19	1,91E-19	1,08E-19	2,39E-48	75	69,07	39,592	6,90598	2,0026
B172	5,8571E-07	5,3525E-06	2,51E-19	7,93E-19	4,29E-45	100	100	68,471	11,0345	2,0049
B173	1,2933E-06	1,1858E-19	8,47E-20	4,07E-20	2,69E-45	50	38,6882	21,753	3,45078	0,5038

B174	7,144E-06	5,5699E-18	2,93E-18	1,53E-20	5,02E-21	75	69,0113	39,464	5,92737	0,5055
B175	5,8099E-07	5,3119E-06	6,57E-19	3,3E-44	9,18E-45	100	100	68,603	10,0691	0,5105
B176	1,3189E-06	2,8459E-19	1,22E-19	3,81E-20	4,57E-44	50	38,707	21,728	3,81012	1,0024
B177	7,1688E-07	5,4528E-19	2,71E-19	4,07E-20	3,81E-48	75	68,8186	39,362	6,21539	1,0044
B178	3,9983E-07	3,7249E-06	6,1E-19	8,54E-15	1,36E-20	100	100	76,673	22,8003	1,0198
B179	1,2917E-06	7,9618E-20	1,61E-19	8,77E-13	5,42E-20	50	38,701	21,924	4,58121	2,0023
B180	7,1107E-07	2,9137E-19	1,81E-19	1,36E-20	3,97E-21	75	69,1856	39,708	6,9293	2,0027
B181	5,8619E-07	5,3574E-06	3,59E-19	1,15E-44	1,04E-47	100	100	68,458	10,8902	2,0048

Table A.2. Results for Toe Filter

Code	Seepage in 100m	Seepage in 200m	Seepage in 300m	Seepage in 400m	Seepage in 500m	Head in 100m	Head in 200m	Head in 300m	Head in 400m	Head in 500m
T101	7,575E-07	2,1683E-19	2,12E-19	1,15E-19	0,010268	50	43,5103	35,901	24,542	11,547
T102	3,5981E-07	4,3366E-19	3,32E-19	1,36E-19	0,010269	75	71,9156	58,079	39,0807	11,548
T103	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED
T104	7,575E-07	3,3203E-19	2,76E-19	9,32E-20	0,001027	50	43,5103	35,901	24,542	11,547
T105	3,6049E-07	3,1509E-19	4,08E-19	3,47E-19	0,001027	75	71,9099	58,05	38,9698	11,548
T106	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED
T107	7,578E-07	1,8973E-19	3,27E-19	1,1E-19	0,000103	50	43,507	35,897	24,5279	11,547
T108	3,6107E-07	5,2175E-19	3,66E-19	3,37E-19	0,000103	75	71,9063	58,019	38,9549	11,548
T109	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED
T110	7,5804E-07	2,9984E-19	3,18E-19	1,34E-19	3,3E-17	50	43,5037	35,895	24,505	8,3934
T111	3,6049E-07	4,8639E-19	5,9E-19	1,9E-19	1,8E-17	75	71,8471	58,043	38,965	9,4406
T112	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED
T113	7,5813E-07	2,0328E-19	2,3E-19	1,83E-19	1,66E-18	50	43,503	35,894	24,5176	8,3944
T114	3,614E-07	2,1344E-19	5,08E-19	2,85E-19	1,94E-18	75	71,8379	58,001	38,8707	9,4406

T115	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED
T116	7,5812E-07	3,388E-19	1,93E-19	1,47E-19	1,9E-19	50	43,503	35,894	24,5104	8,3906
T117	3,6068E-07	5,7255E-19	4,27E-19	2,42E-19	3,39E-20	75	71,845	58,035	38,9433	9,4406
T118	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED
T119	7,5832E-07	2,2022E-19	2,02E-19	1,1E-19	1,04E-17	50	43,499	35,891	24,5208	3,0613
T120	3,6211E-07	3,9976E-19	4,59E-19	2,03E-19	5,57E-35	75	71,6898	58,012	38,8369	3,0656
T121	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED
T122	7,5837E-07	1,2366E-19	2,57E-19	2,59E-19	5,61E-19	50	43,4987	35,89	24,5208	3,0734
T123	3,6185E-07	5,3186E-19	3,62E-07	2,91E-19	1,35E-35	75	71,692	58,024	38,8631	3,071
T124	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED
T125	7,5839E-07	1,1858E-19	2,74E-19	2,25E-19	2,09E-20	50	43,4983	35,89	24,5178	3,0787
T126	3,6177E-07	6,9793E-19	5,37E-19	3,25E-19	1,14E-30	75	71,6925	58,028	38,8706	3,0728
T127	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED
T128	8,8122E-07	2,8798E-19	1,8E-19	1,52E-20	5,27E-17	50	42,5743	33,086	18,1506	17,579
T129	4,2921E-07	6,6744E-19	2,17E-19	1,49E-19	1,14E-16	75	71,4089	54,524	29,1643	17,578
T130	3,0052E-07	2,8214E-06	3,52E-19	2,85E-19	9,68E-17	100	100	81,081	44,051	17,594
T131	8,8928E-07	3,117E-19	1,12E-19	1,64E-19	9,82E-18	50	42,506	32,932	17,8746	17,579
T132	4,2885E-07	4,9126E-19	2,85E-19	1,32E-19	1,3E-17	75	71,412	54,547	29,2096	17,578
T133	3,0105E-07	2,8264E-06	3,79E-19	1,76E-19	9,11E-18	100	100	81,056	44,0514	17,594
T134	8,7854E-07	3,117E-19	1,76E-19	4,24E-20	6,37E-19	50	42,5969	33,136	18,2562	17,579
T135	4,2917E-07	6,4033E-19	2,54E-19	2,1E-19	1,3E-17	75	71,4094	54,532	29,2427	17,578
T136	3,0017E-07	2,8181E-06	4,27E-19	3,74E-19	9,48E-19	100	100	81,108	46,5399	17,594
T137	8,829E-07	3,1509E-19	3,05E-19	8,3E-20	1,02E-16	50	42,5554	33,072	19,0774	11,613
T138	4,2979E-07	4,5322E-19	3,86E-19	1,08E-19	2,26E-17	75	71,4054	54,57	29,5106	11,15
T139	3,02E-07	2,835E-06	5,08E-19	2,22E-19	7,98E-17	100	100	80,971	44,1305	11,236
T140	8,818E-07	2,7443E-19	3,18E-19	7,96E-20	5,85E-18	50	42,5642	33,098	19,374	11,596

T141	4,3039E-07	4,5308E-19	5,32E-19	2,09E-19	1,51E-18	75	71,4003	54,542	29,4508	11,255
T142	3,0184E-07	2,8335E-06	2,91E-19	3,35E-19	1,73E-18	100	100	80,984	44,444	12,243
T143	8,8054E-07	1,3213E-19	3,29E-19	1,69E-20	3,39E-19	50	42,5748	33,122	19,3947	12,197
T144	4,301E-07	6,228E-19	3,66E-19	1,39E-19	3,38E-19	75	71,4028	54,556	29,6073	11,324
T145	3,0203E-07	2,8353E-06	4,68E-19	3,59E-19	9,29E-19	100	100	80,973	44,2249	12,502
T146	7,9131E-07	1,8634E-19	2,41E-19	1,21E-19	2,08E-17	50	43,1953	35,107	25,0262	3,7783
T147	4,3187E-07	5,5394E-19	2,13E-19	1,96E-19	5,2E-18	75	71,3051	54,432	30,7141	3,7906
T148	3,0483E-07	2,8608E-06	4,91E-19	2,44E-19	3,47E-18	100	100	80,914	43,3429	2,0575
T149	8,8407E-07	1,5924E-19	1,73E-19	4,4E-20	6,5E-19	50	42,5472	33,164	22,9341	1,1034
T150	4,3354E-07	5,1328E-19	3,22E-19	1,22E-19	4,34E-19	75	71,2898	54,374	30,3146	1,5994
T151	3,0519E-07	2,8642E-06	3,18E-19	2,98E-19	2,15E-19	100	100	80,895	43,1517	1,289
T152	8,935E-07	1,5924E-19	1,58E-19	5,93E-20	1,36E-20	50	42,4707	32,973	22,3046	3,1543
T153	4,3303E-07	6,8946E-19	3,49E-19	1,46E-19	4,23E-35	75	71,296	54,35	30,6258	2,3895
T154	3,0474E-07	2,86E-06	3,83E-19	1,15E-19	1,59E-21	100	100	80,915	43,2389	1,4906
T155	1,063E-06	2,6765E-19	1,52E-19	1,79E-17	1,25E-16	50	41,0961	29,024	18,1739	26,384
T156	5,3945E-07	6,6402E-19	4,49E-19	5,72E-17	1,41E-16	75	70,4052	48,903	22,0234	26,381
T157	3,9938E-07	3,7206E-06	2,49E-19	2,03E-17	1,8E-16	100	100	76,748	28,7903	26,276
T158	1,063E-06	2,6088E-19	1,69E-19	5,59E-18	1,73E-17	50	41,0961	29,024	18,1739	26,384
T159	5,3788E-07	2,9466E-19	2,3E-19	3,17E-18	1,49E-17	75	70,4199	48,94	22,1051	26,381
T160	3,9946E-07	3,7212E-06	2,64E-19	5,19E-18	1,11E-17	100	100	76,66	28,6653	26,276
T161	1,063E-06	2,6426E-19	1,66E-19	3,25E-19	6,33E-19	50	41,0961	29,024	18,1739	26,384
T162	5,3757E-07	6,9624E-19	4,9E-19	2,89E-20	9,69E-19	75	70,4186	48,98	22,1357	26,381
T163	3,9903E-07	3,7175E-06	3,04E-19	1,9E-19	-1,53E-19	100	100	76,722	28,6606	
T164	1,0661E-06	4,4383E-19	1,17E-19	0,004489	5,29E-17	50	41,0688	29,764	39,1947	17,407
T165	5,3834E-07	6,3016E-19	4,18E-19	0,0022	1,91E-17	75	70,1749	49,127	40,6436	14,504
T166	4,0251E-07	3,7499E-06	7,1E-19	0,013662	7,64E-17	100	100	76,609	43,8183	20,073

T167	1,0631E-06	3,4897E-19	2,39E-19	1,63E-17	1,56E-17	50	41,0944	29,752	39,3045	16,223
T168	5,386E-07	7,1063E-19	3,35E-19	0,002164	1,04E-17	75	70,1747	49,116	39,8555	21,503
T169	4,0219E-07	3,7458E-06	3,66E-19	0,001716	1,92E-17	100	100	76,63	41,6212	21,401
T170	1,0626E-06	3,6252E-19	1,22E-19	4,26E-06	1,33E-18	50	41,0994	29,792	39,4525	14,367
T171	5,3832E-07	5,0819E-19	4,18E-19	8,59E-05	1,23E-18	75	70,1748	49,136	40,5198	17,554
T172	4,0208E-07	3,7457E-06	4,79E-19	0,000191	9,45E-19	100	100	76,606	43,1642	21,461
T173	8,6657E-07	1,7956E-19	1,46E-19	4,34E-19	2,43E-17	50	42,6746	34,217	47,108	3,9831
T174	5,4448E-07	4,4712E-19	1,32E-19	6,94E-18	1,73E-18	75	70,3598	49,547	42,9621	1,6457
T175	4,0832E-07	3,8E-06	2,78E-19	6,85E-17	9,53E-18	100	100	76,307	41,7133	4,8462
T176	1,0493E-06	1,7279E-19	2,51E-19	8,67E-19	9,99E-20	50	41,2073	32,023	39,9402	3,9414
T177	5,4006E-07	3,93E-19	3,05E-19	4,34E-19	1,63E-18	75	70,4036	49,693	41,5781	6,6615
T178	4,0967E-07	3,8118E-06	2,85E-19	1,4E-18	2,16E-19	100	100	76,221	32,2866	2,9788
T179	1,0543E-06	3,6252E-19	1,59E-19	5,42E-20	4,07E-20	50	41,0331	29,163	40,8241	1,5057
T180	5,4288E-07	3,3879E-19	3,59E-19	4,07E-21	7,45E-20	75	70,3788	49,529	44,0439	2,9854
T181	4,0947E-07	3,8106E-06	4,11E-19	1,9E-19	4,67E-20	100	100	76,145	35,6246	3,2927

Table A.3. Results for Chimney Filter

Code	Seepage in 100m	Seepage in 200m	Seepage in 300m	Seepage in 400m	Seepage in 500m	Head in 100m	Head in 200m	Head in 300m	Head in 400m	Head in 500m
C101	7,6541E-09	1,8548E-19	7,61E-19	4,29E-45	1,73E-18	50	49,9369	39,43	4,46383	0,504
C102	3,4284E-09	4,126E-19	8,67E-19	7,09E-47	1,73E-18	75	74,9744	53,027	5,24764	0,5048
C103	2,6642E-09	2,2701E-08	8,14E-19	4,33E-45	1,73E-18	100	100	69,286	6,46056	
C104	2,8683E-09	2,7461E-19	1,01E-46	2,05E-46	3,36E-18	50	49,9759	30,369	4,23742	1,0032
C105	7,8396E-10	5,3023E-19	8,07E-47	6,39E-44	3,36E-18	75	74,9936	34,895	4,53155	1,0035
C106	5,8289E-10	4,4839E-09	1,12E-46	5,87E-44	3,36E-18	100	100	38,083	4,61351	1,0035
C107	2,7965E-09	2,4134E-19	2,96E-44	2,13E-10	3,65E-18	50	49,9765	31,285	5,13597	2,0017

C108	7,7704E-10	4,7301E-19	1,23E-46	2,13E-10	3,63E-44	75	74,9938	35,067	5,26917	2,0018
C109	5,7566E-10	4,4283E-09	3,47E-18	2,13E-10	3,65E-18	100	100	39,18	5,56079	2,0019
C110	7,6541E-09	2,3708E-19	1,24E-46	3,85E-19	2,56E-19	50	49,9369	39,935	4,4983	0,5041
C111	3,5011E-09	5,3297E-19	2,17E-19	3,56E-19	2,82E-19	75	75	51,519	5,08631	0,5046
C112	3,1736E-09	2,9431E-08	5,08E-44	3,85E-19	2,56E-19	100	100	43,973	4,97808	0,5045
C113	2,8683E-09	2,0674E-19	2,48E-44	2,17E-19	5,16E-19	50	49,9759	30,128	4,19362	1,0032
C114	7,8396E-10	3,9087E-19	3,05E-19	2,17E-19	5,16E-19	75	74,9936	34,711	4,50349	1,0034
C115	5,8289E-10	4,4839E-09	1,02E-19	2,17E-19	5,16E-19	100	100	38,143	4,6053	1,0035
C116	2,7964E-09	1,9954E-19	1,3E-45	2,13E-11	4,16E-48	50	49,9765	31,434	5,10351	2,0017
C117	7,7704E-10	3,2933E-19	1,52E-44	2,13E-11	4,54E-44	75	74,9938	34,492	5,15485	2,0017
C118	5,7566E-10	4,4282E-09	3,19E-19	2,13E-11	4,8E-44	100	100	39,643	5,58139	2,002
C119	7,6541E-09	2,5825E-19	7,19E-21	1,13E-46	2,49E-21	50	49,9369	39,775	4,4628	0,504
C120	3,4283E-09	5,5133E-19	1,36E-20	1,74E-46	7,52E-21	75	74,9744	53,237	5,26839	0,5048
C121	2,8794E-09	2,521E-08	1,91E-20	2,04E-45	2,49E-21	100	100	63,143	5,91266	0,5055
C122	2,8683E-09	3,7429E-19	8,3E-21	3,3E-20	8,3E-22	50	49,9759	31,201	4,33719	1,0033
C123	7,8394E-10	3,0492E-19	1,05E-46	3,3E-20	8,3E-22	75	74,9936	34,873	4,53432	1,0035
C124	5,8288E-10	4,4837E-09	1,36E-20	4,08E-20	8,3E-22	100	100	38,757	4,75183	1,0037
C125	2,7963E-09	2,1393E-19	2,49E-21	2,13E-12	3,53E-20	50	49,9765	31,458	5,15882	2,0017
C126	7,7701E-10	3,15E-19	2,2E-44	2,13E-12	3,69E-20	75	74,9938	35,137	5,30785	2,0018
C127	5,7564E-10	4,4281E-09	2,37E-44	2,13E-12	3,53E-20	100	100	39,835	5,58673	2,002
C128	7,4332E-09	2,2658E-19	9,74E-19	1,04E-18	2,5E-18	50	52,2881	55,889	5,52806	0,5059
C129	3,379E-09	2,4793E-19	1,27E-18	1,04E-18	2,5E-18	75	74,9722	56,051	5,58272	0,5059
C130	2,9114E-09	2,5482E-08	1,02E-46	1,04E-18	2,5E-18	100	100	60,948	5,72737	0,5061
C131	7,3368E-09	2,4025E-19	3,95E-10	3,14E-10	1,26E-10	50	52,2202	55,876	5,85921	1,0039
C132	3,3745E-09	3,1557E-19	3,95E-10	3,14E-10	1,01E-10	75	74,9722	55,459	5,88994	1,004
C133	2,9089E-09	2,5464E-08	3,95E-10	3,14E-10	1,01E-10	100	100	60,688	5,99681	1,0041

C134	2,7962E-09	2,1573E-19	6,41E-43	1,43E-18	3,34E-18	50	49,9765	51,941	6,56019	2,0027
C135	7,77E-10	1,6877E-19	7,08E-19	1,43E-18	3,34E-18	75	74,9938	54,86	6,74453	2,0028
C136	5,7564E-10	4,4281E-09	1,76E-20	1,43E-18	3,34E-18	100	100	54,57	6,48713	2,0027
C137	7,4332E-09	2,8857E-19	6,17E-47	2,88E-20	4,83E-45	50	52,2855	55,595	5,48729	0,5058
C138	3,3791E-09	4,2725E-19	4,41E-21	4,06E-44	6,72E-48	75	74,9722	56,125	5,54391	0,5059
C139	2,9309E-09	2,5769E-08	8,36E-22	9,25E-47	3,56E-47	100	100	59,611	5,6635	0,506
C140	7,3318E-09	2,2083E-19	3,95E-11	3,14E-11	1,26E-11	50	52,2243	56,326	6,03428	1,004
C141	3,375E-09	3,3552E-19	3,95E-11	3,14E-11	1,01E-11	75	74,9722	55,214	5,81952	1,0039
C142	2,9312E-09	2,5794E-08	3,95E-11	3,14E-11	1,01E-11	100	100	59,763	6,04626	1,0041
C143	2,7962E-09	2,8378E-19	4,07E-19	4,47E-20	1E-19	50	49,9765	51,661	6,60481	2,0028
C144	7,7699E-10	2,9378E-19	2,5E-19	1,15E-19	1E-19	75	74,9938	54,117	6,66155	2,0028
C145	5,7564E-10	4,428E-09	1,33E-19	5,75E-20	1E-19	100	100	55,295	6,64324	2,0028
C146	7,4361E-09	1,674E-19	1,75E-46	1,44E-46	1,09E-44	50	52,18	55,618	5,47504	0,5058
C147	3,3803E-09	3,0893E-19	2,19E-44	1,48E-44	4,01E-48	75	74,9722	55,788	5,56948	0,5059
C148	2,9325E-09	2,5794E-08	6,36E-21	7,43E-47	4E-48	100	100	59,346	5,67273	0,506
C149	7,3244E-09	2,2337E-19	3,95E-12	3,14E-12	1,26E-12	50	52,227	55,95	5,89028	1,0039
C150	3,3751E-09	2,8903E-19	3,95E-12	3,14E-12	1,01E-12	75	74,9722	55,711	6,0422	1,0041
C151	2,927E-09	2,573E-08	3,95E-12	3,14E-12	1,01E-12	100	100	59,226	6,12986	1,0042
C152	2,7961E-09	1,553E-19	1,11E-20	1,99E-20	2,4E-20	50	49,9765	51,712	6,52834	2,0027
C153	7,7697E-10	4,9049E-19	5,97E-20	1,99E-20	2,4E-20	75	74,9938	53,687	6,54813	2,0027
C154	5,7562E-10	4,4279E-09	1,67E-44	1,99E-20	2,4E-20	100	100	55,245	6,5792	2,0027
C155	7,2905E-09	2,4024E-19	6,91E-47	1,73E-46	1,53E-18	50	53,5	64,014	6,00034	0,505
C156	3,3226E-09	4,1631E-19	9,51E-45	8,05E-45	1,53E-18	75	74,9729	62,491	5,81243	0,5048
C157	2,9177E-09	2,5579E-08	1,42E-46	1,1E-46	1,53E-18	100	100	62,743	5,85038	0,5048
C158	7,147E-09	1,6076E-19	4,92E-20	1,17E-18	1,63E-18	50	53,5563	61,535	5,83001	1,0042
C159	3,3154E-09	2,1165E-19	3,82E-18	1,73E-18	1,63E-18	75	74,973	63,181	6,28316	1,0045

C160	2,9141E-09	2,5544E-08	2,6E-18	1,17E-18	1,63E-18	100	100	63,304	6,18403	1,0045
C161	7,0427E-09	2,0943E-19	1,03E-46	4,18E-18	4,27E-18	50	53,4274	64,889	7,16808	2,0029
C162	3,306E-09	6,6108E-19	2,97E-18	4,18E-18	4,27E-18	75	74,973	65,238	7,05165	2,0029
C163	2,9077E-09	2,5496E-08	9,27E-45	4,18E-18	4,27E-18	100	100	64,374	6,99765	2,0028
C164	7,2919E-09	1,0351E-19	1,12E-46	2,88E-20	2,61E-19	50	53,5147	62,544	5,79066	0,5048
C165	3,3223E-09	2,5452E-19	5,65E-47	2,53E-45	2,61E-19	75	74,9729	62,592	5,85459	0,5048
C166	2,9177E-09	2,5579E-08	3,17E-33	2,02E-46	2,61E-19	100	100	63,119	5,82778	0,5048
C167	6,9989E-09	3,1732E-19	1,02E-46	5,75E-20	5,23E-20	50	53,5213	64,012	6,32309	1,0046
C168	3,314E-09	2,9068E-19	3,52E-19	5,18E-19	7,45E-48	75	74,973	21,756	3,90447	1,0039
C169	2,9141E-09	2,5545E-08	8,39E-47	5,75E-20	5,23E-20	100	100	62,883	6,26439	1,0046
C170	6,8314E-09	1,3959E-19	1,73E-19	2,68E-19	2,83E-19	50	53,1642	64,365	7,35939	2,003
C171	3,3033E-09	3,9446E-19	2,68E-42	2,68E-19	2,83E-19	75	74,973	63,956	6,91355	2,0028
C172	2,9071E-09	2,5488E-08	4,5E-19	2,68E-19	2,83E-19	100	100	2,0001	2,0001	2,0001
C173	7,2632E-09	1,7873E-19	7,35E-45	1,66E-46	2,71E-20	50	53,4827	63,259	5,8638	0,5048
C174	3,3216E-09	3,0098E-19	3,59E-44	1,08E-46	2,71E-20	75	74,9729	63,41	5,89344	0,5049
C175	2,9177E-09	2,5579E-08	7,08E-44	1,45E-46	2,71E-20	100	100	63,393	5,8742	0,5048
C176	6,6953E-09	2,8842E-19	7,52E-47	2,95E-20	5,62E-48	50	53,3094	62,6	6,44283	1,0092
C177	3,3123E-09	2,5479E-19	9,3E-45	2,84E-20	4,26E-44	75	74,973	62,663	6,07551	1,0044
C178	2,9141E-09	2,5544E-08	8,18E-47	2,84E-20	3,36E-44	100	100	63,419	6,21119	1,0045
C179	6,9984E-09	1,7978E-19	5,81E-21	2,39E-20	4,28E-20	50	53,2714	63,875	6,95258	2,0028
C180	3,3126E-09	7,0616E-19	4,7E-37	2,39E-20	4,28E-20	75	74,973	63,455	6,95547	2,0028
C181	2,907E-09	2,5486E-08	7,5E-20	2,39E-20	4,28E-20	100	100	67,291	7,24254	2,003

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