ASSESSMENT OF PERFORMANCE OF DRAINAGE SYSTEMS IN EARTH-FILL DAMS

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

AHSEN NUR YILMAZ

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
CIVIL ENGINEERING

MARCH 2017

Approval of the thesis:

ASSESSMENT OF PERFORMANCE OF DRAINAGE SYSTEMS IN EARTH-FILL DAMS

submitted by **AHSEN NUR YILMAZ** in partial fulfillment of the requirements for the degree of **Master of Science in Civil Engineering Department, Middle East Technical University** by,

Prof. Dr. Gülbin Dural Ünver ____________________
Dean, Graduate School of **Natural and Applied Sciences**

Prof. Dr. İsmail Özgür Yaman ____________________
Head of Department, **Civil Engineering**

Prof. Dr. A. Melih Yanmaz ____________________
Supervisor, **Civil Engineering Department, METU**

Asst. Prof. Dr. Melih Çalamak ____________________
Co-supervisor, **Civil Engineering Department, TEDU**

Examining Committee Members:

Assoc. Prof. Dr. Nuri Merzi ____________________
Civil Engineering Dept., METU

Prof. Dr. A. Melih Yanmaz ____________________
Civil Engineering Dept., METU

Asst. Prof. Dr. Melih Çalamak ____________________
Civil Engineering Dept., TEDU

Asst. Prof. Dr. Onur Pekcan ____________________
Civil Engineering Dept., METU

Asst. Prof. Dr. Müsteyde Baduna Koçyiğit ____________________
Civil Engineering Dept., Gazi University

Date: *March 13, 2017*

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.

Name, Last name: Ahsen Nur YILMAZ

Signature :

ABSTRACT

ASSESSMENT OF PERFORMANCE OF DRAINAGE SYSTEMS IN EARTH-FILL DAMS

Yılmaz, Ahsen Nur

M.Sc., Department of Civil Engineering

Supervisor : Prof. Dr. A. Melih Yanmaz

Co-Supervisor: Asst. Prof. Dr. Melih Çalamak

March 2017, 112 pages

Earth-fill dams are exposed to seepage throughout their lifetime. In many cases, seepage related safety precautions needed are to be taken to keep seepage rate and pore water pressures below certain limits. This is commonly handled by installation of drainage facilities which are blanket, chimney and toe drains. This study is aimed at finding suitability and the effectiveness of drainage facilities in earth-fill dams. For this purpose, various materials and geometries are considered for different drain types in separate cases. Steady-state seepage analyses are conducted using a finite element software. Results showed that increased length of blanket drain causes increased seepage flow and shorter path of phreatic line, whereas the effect of thickness of blanket drain can be neglected. The results also showed that coarser material gradation of chimney drain causes steeper phreatic line through the core. Increased height of the toe drain results in higher seepage rates through the dam. Material gradation of toe drain has not a distinct role on its performance.

Keywords: Earth-fill dams, seepage analysis, pore water pressure, drainage system, performance

ÖZ

TOPRAK DOLGU BARAJLARIN DRENAJ SİSTEMLERİNİN PERFORMANSININ DEĞERLENDİRİLMESİ

Yılmaz, Ahsen Nur
Yüksek Lisans, İnşaat Mühendisliği Bölümü
Tez Yöneticisi : Prof. Dr. A. Melih Yanmaz
Ortak Tez Yöneticisi : Yard. Doç. Dr. Melih Çalamak

Mart 2017, 112 sayfa

Toprak dolgu barajlar drenaj ömürleri boyunca sızmaya maruz kalırlar. Birçok durumda, boşluk suyu basıncını ve sızma miktarını belirli sınırların altında tutmak için sızmayla ilgili emniyet önlemleri alınmalıdır. Bu genellikle yatay, düşey ve topuk drenaj tesislerinin kurulmasıyla çözümlenir. Bu çalışma toprak dolgu barajlardaki drenaj tesislerinin uygunluğunu ve etkinliğini bulmayı araştırmaktadır. Bu amaçla, çeşitli malzeme ve geometriler farklı dren tipleri için ayrı ayrı dikkate alınmıştır. Kararlı durum sızma analizi, sonlu elemanlar yazılımı kullanılarak yürütülmüştür. Sonuçlar, yatay drenin artan uzunluğunun sızıntı akışının artmasına ve sızma hattının daha kısa olmasına neden olduğunu göstermektedir. Bununla birlikte yatay dren kalınlığının etkisi ihmal edilebilir. Sonuçlar aynı zamanda düşey drenin kaba malzeme gradasyonunun çekirdekte daha dik bir sızma hattına neden olduğunu göstermektedir. Artırılmış topuk dreni yüksekliği baraj boyunca yüksek sızıntı oranlarına sebep olmaktadır. Topuk dreni malzeme gradasyonunun drenaj performansı üzerinde belirgin bir rolü yoktur.

Anahtar Kelimeler: Toprak dolgu baraj, sızma analizi, boşluk suyu basıncı, drenaj sistemleri, performans

To my family members Asya, Leman and Bekir BİNGÖL

ACKNOWLEDGEMENTS

I would like to express my respect and gratitude to my advisor Prof. Dr. A. Melih Yanmaz. He gave me valuable comments to finalize this study. I would like to thank Dr. Yanmaz for his guidance.

I would like to thank my thesis co-advisor Asst. Prof. Dr. Melih Çalamak. He always motivated me with his positive energy. Without weekly meeting and his support this thesis could not be completed on time. The door to Dr. Çalamak was always open to me whenever I had a trouble spot. I am really glad to study with him.

My bosses: Civil Engineers M. Engin Güninindi, M.Sc., Dursun Özsaraç, M.Sc., and Murat Şahin, M.Sc. encouraged me to start this master program and continuously followed the processes in my study. I thank all of them for giving me a good perspective in applied engineering problems. I also thank Berk Demir who guided me to the right geotechnical references. My friends and my big family are the silent supporters of me and they always tolerated our never ending postponed meetings due to my hard work load.

Special and deeply thanks to my sister Asya, and my parents Leman and Bekir Bingöl. They always support me during my bad and good times. Being their child and being a part of that love is really valuable for me. My father calmed me with his didactic stories and my mother prepared everything for me to study freely and easily after work. All this time I had a full-time job, thesis study and my marriage preparation and they handled most of the things. I always feel their love.

Final thanks to my husband, my love and my best friend Esat. He was really calm, supportive and always with me. I love him very deeply.

TABLE OF CONTENTS

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

B	The base width of the dam [m]
b	The base width of impervious core [m]
c	Upstream side slope
C	Clay
CH	Clays of High Plasticity- Compacted
CL	Clays of Low Plasticity- Compacted
D_{15}	Particle size finer than 15% of the material [mm]
d	Downstream slope cover [m]
d^*	A non-dimensional parameter of downstream slope cover
D/S	Downstream
e	Downstream side slope
E	Modulus of elasticity [kPa]
F_B	Freeboard [m]
F_B^*	A non-dimensional parameter of the freeboard
GC	Clayey Gravels, Clayey Sandy Gravels
GM	Silty Gravels, Silty Sandy Gravels
GP	Poorly Graded Gravel
GW	Well Graded Gravel
H	The height of dam [m]
h	The height of toe drain [m]
h_t	Total head [m]
h_p	Pressure head [m]
h_w	Reservoir water height [m]
i	Hydraulic gradient
K	Hydraulic conductivity [m/s]
K_H	Horizontal hydraulic conductivity [m/s]

K_V	Vertical hydraulic conductivity [m/s]
K_r	Relative hydraulic conductivity [-]
K_s	Saturated hydraulic conductivity [m/s]
L	Length of drain [m]
L_{min}	Minimum length of drain [m]
L_{min}^*	A non-dimensional parameter of minimum length of drain
L_{max}	Maximum length of drain [m]
L_{max}^*	A non-dimensional parameter of maximum length of drain
m	A fitting parameter of van Genuchten method
n	A fitting parameter of van Genuchten method
MS	Medium Grained Sand
SM	Silty Sands
SP	Poorly Graded Sands
S_p	Slope of the hydraulic conductivity function curve
SW	Well Graded Sands
T	The top width of the dam [m]
T^*	A non-dimensional parameter of top width of the dam
t'	Time
t	Thickness of the drain
Q	Applied boundary flux [m^3/s]
q	Unit discharge [m^3/s/m]
U/S	Upstream
x	Horizontal distance [m]
y	Vertical distance [m]
θ	Volumetric water content
θ_s	Saturated water content
θ_r	Residual water content
Θ	Dimensionless water content
α	A fitting parameter of van Genuchten method
γ	Unit weight [kN/m^3]

μ	Poisson's ratio

CHAPTER 1

INTRODUCTION

1.1 General

Earth-fill dams are composed of porous materials. Due to the difference in the water levels of upstream and downstream sides, there always exists seepage through the body of these dams. The quantity of seepage is important not only for the prevention of excessive losses from the reservoir volume but also for the safety of the dam. Statistics show that seepage related problems are the most common reason for the earth-fill dam failures (Foster et al. 2000). Seepage related major problems in earth-fill dam are piping, downstream sloughing and high pore water pressures within the dam. Piping is an internal soil erosion initiated by seepage (Sharma and Kumar 2013). In this manner, commonly rapid failure of dam is observed (Taft, Speck and Morris 1994). Teton Dam and Baldwin Hills Dam disasters are two examples of the piping failure (Sharma and Kumar 2013). The other problems caused by seepage are downstream sloughing and the existence of high pore water pressures. Therefore, seepage through earth-fill dams should be kept under control.

Excessive pore water pressures may cause increased uplift forces in the slopes of the dam. This may result in reduced slope stabilities. An extended seepage face and excessive seepage quantities may wash the embankment material at the downstream face of the dam. These make the embankment more vulnerable to a possible slope failure (Singh and Varshney 1995; USBR 2011a). It is well known that the downstream part should be kept unsaturated since it supports the central part of the dam (USBR 2011a). In order to keep downstream part dry, prevent high pore water pressures, and reduce the phreatic line elevations drainage facilities are needed (Justin 1932; Sherard 1963). The elevation of phreatic line in an earth-fill dam can be reduced either by implementing drainage facilities or by constructing an impervious core (Singh and Varshney 1995). The impervious zone reduces seepage quantity whereas drainage facilities provide a safe route for water drainage from the body. In some cases, even when an impervious core exists, a drainage facility might be needed (Singh and Varshney 1995). It is stated in USBR (2011a) that a steady-state analysis is sufficient for analyzing seepage flow quantities, gradients and pore water pressures in an earth-fill dam under normal operation conditions.

Commonly, three drainage types are applied in earth-fill dams, i.e. blanket, chimney, and toe drains. The materials of drains are composed of gravel-size materials (FEMA 2011) which are generally more permeable than the shell material of the dam body. The effectiveness of a drain facility in decreasing the seepage flow and pore water pressures are related with its material and geometric properties and the present study investigates the performance of these facilities.

1.2 Literature Review

Earth-fill dams have been constructed from the early times of human being. As an advantage of this long time design experiences, drainage systems are studied by several researchers using experimental, numerical and analytical methods. In the literature, following studies exist about the drainage structures used in embankment dams.

The proper design of blanket drains was studied by Chahar (2004) by an analytical solution technique. He obtained explicit equations to determine downstream slope cover and the length of the blanket drain using geometrical properties of the dam cross-section. The study resulted that downstream slope cover was affected by the geometry of the dam. A non-dimensional equation was given for the determination of the length of horizontal downstream drainage filter for a given dam section and for a specified downstream slope cover. It was found that the distance between phreatic line and downstream cover was affected by length of blanket drain. The determination of the length of the blanket drain in simple zoned earth-fill dam was studied by Mansuri and Salmasi (2013). Numerical analyses were conducted by SEEP/W software (Geo-Slope Int Ltd 2015) for varying lengths and cut off wall systems. The aim of the study was to find out the effect of seepage on uplift pressures and hydraulic gradients in a proposed simple zoned earth-fill dam. It was found that when the length of the blanket drain increased, the seepage flow and hydraulic gradients through dam body increased. Mishra and Singh (2005) defined a dry zone area which was the zone between phreatic line and downstream slope in a homogenous dam having a blanket drain. The study stated that, dry zone area was related with the length of the drain and the capillary saturation. The location of the drain was shown to have an effect on the capillary rise above phreatic line and downstream stability. If the upstream slope was milder, safety of the capillary rose and stability of downstream slope might have been sustained with a smaller drain length.

The thickness of the blanket drain is another important geometric property for its performance. An experimental study was carried out by Malekpour et al. (2012) to investigate the effects of the thickness and length of the blanket drain for steady-state and transient seepage conditions and the slope stability of a low permeable homogenous dam. It was resulted that, when the thickness increased, the probability of piping decreased for the steady-state flow conditions. The thickest drain was found to be the most protective alternative. However, downstream slope cover was shown to be not affected by the increase of the blanket drain thickness. The results also showed that, increasing the thickness of the drain might efficiently decrease the excessive pore water pressures throughout the body and might help protecting the dam from piping. Besides, it was found that, if the length of the blanket drain with constant thickness increased, the phreatic line elevations decreased in the downstream part of the dam. The effective length of the horizontal drain was also studied with a numerical method by Mansuri and Salmasi (2013) in a simple zoned earth-fill dam. They investigated the effects of length of the blanket drain on pore water pressures and hydraulic gradients. Two-dimensional numerical solution of the governing equation of the seepage was conducted by SEEP/W software (Geo-Slope Int Ltd 2015) with finite element method. It was shown that if length of blanket drain was increased, the seepage rate was increased and piping risk was reduced. Total uplift pressures were obtained and it was found that the changes at pressures in the core were negligible when the length of blanket drain increased. The findings were also showed that when the length of blanket drain was increased, the exit hydraulic gradients at the toe were increased.

Maslia and Aral (1982) investigated the performance of the chimney drain in a simple zoned earth-fill dam. A numerical model was used to analyze the steady-state seepage flow with saturated/unsaturated soil model. In the study, the hydraulic conductivity of the drain and the reservoir level were varied and the location of the free surface, the seepage quantity and the velocity and pressure distributions were investigated. It was shown that when the hydraulic conductivity increased the flow rate increased. Also, when the reservoir level increased, the elevation of the free surface and the hydrostatic uplift pressures increased. Furthermore, increasing the reservoir level caused a seepage face in the downstream face even various hydraulic conductivity values were assigned to the drain. Therefore, it was concluded that the reservoir level also effected the performance of the chimney drain.

The findings of experimental studies on the chimney drain were presented in Djehiche et al. (2014) and Djehiche et al. (2012). A homogenous type earth-fill dam was modeled in laboratory and experiments were conducted under steady-state flow conditions. Djehiche et al. (2012) obtained that the location of the chimney drain in an earth-fill dam resting on an impervious foundation depended on the maximum head at the upstream, the drain height, and the slope of the upstream face. It was found that the flow rate passing through a chimney drain was related with the reservoir level, horizontal permeability of dam, the foundation type, and the slope of the upstream side. The seepage rate results of the experimental and analytical models were agreed well, and showed that steeper upstream slopes caused higher discharges in the chimney drain. Djehiche et al. (2014) investigated the most effective flow rate of the drains in earth-fill dams resting on a pervious foundation using experimental, analytical and numerical techniques. Djehiche et al. (2014) extended the same study with a numerical solution approach by using SEEP/W software (Geo-Slope Int Ltd. 2014a). It was found that numerical solution agreed with experimental and analytical solutions which were found in the previous study.

In the study of Mishra and Parida (2006), the geometry of toe drains in homogeneous earth-fill dams resting on impervious foundations were determined with an analytical method. It was resulted that the reservoir water level, capillary rise of the seepage in the embankment soil, the dam geometry, and the tailwater position affected the toe drain height. The downstream slope was shown to be affected by capillary saturation of the system. When the capillary saturation increased, toe drain height was needed to be increased. Additionally, it was seen that the height of the tailwater directly affected the height of toe drain. Increasing the height of the tailwater level resulted in greater toe drain heights. Mishra and Parida (2006) recommended toe drain height to be equal to one third of the reservoir water level height. The study of Creager et al (1945), which recommended a toe drain height equal to one third of the dam height, were stated to overestimate the toe drain height. Similar findings were presented in Singh and Varshney (1995), which recommended the height of the toe drain to be one fourth to one third of the reservoir water level. Abdul Hussain et al. (2007) studied the optimization of the earth-fill dam geometry which had a toe drain under sudden filling and drawdown conditions. The results of the study showed that 2% of the dam height as the toe drain height was enough for an effective drainage. It was also shown that the dam height directly affected the upstream and downstream side slopes.

1.3 The Aim and Scope of the Study

The aim of this study is to determine the effectiveness of blanket, chimney and toe drains in earth-fill dams and to determine the effects of geometrical and material properties of these facilities on seepage behavior of the dams. Even though many studies about drainage facilities of earth-fill dams exist, there is a gap in determination of the performance of these structures. Also, no previous study dealt with comparison of the effectiveness of the drainage structures. To this end, seepage analyses are conducted on a realistic hypothetical earth-fill dam. The dam is considered to be homogeneous and simple zoned types for the same geometrical properties in separate cases. Steady-state seepage analyses are conducted for these two layouts with different drainage facilities having various geometrical and material properties. The phreatic surface profiles, variation of pore water pressures at predefined points and the seepage flow passing through the dam body are assessed and compared to meet the aim of the study.

The performance of the blanket drain is assessed by varying its geometrical properties which are characterized by length and thickness of the drain. The performance of chimney drain is also dependent on its geometry and material properties. The effectiveness of this drain is investigated by applying it on the simple zoned dam. Its thickness, the downstream slope of the core layer and the hydraulic conductivity of the drain are varied considering the design limitations. For the toe drain, two different layouts are considered. In the first layout, the toe drain is placed in a trench under a blanket drain and under a chimney drain as a supplementary drainage structure. The effectiveness of the drain is compared for these two arrangements. In the second one, it is applied as a separate individual drainage facility in the homogenous dam. For this layout, the height and the hydraulic conductivity of the drain are varied. The seepage analyses of the current study are conducted with a finite element software, SEEP/W (Geo-Slope Int Ltd 2015). It is based on numerical solution of partial differential equation of the flow in porous media. The analyses results yield the profile of the phreatic surface, pore water pressures, and the seepage flow passing through the dam body. The detailed information about the software is provided in the third chapter.

CHAPTER 2

DRAINAGE FACILITIES USED IN EARTH-FILL DAMS

Homogenous and simple zoned type earth-fill dams are designed with appropriate drainage facilities, i.e. blanket, chimney, and toe drains in order to discharge the seepage safely from the dam. These facilities have significant role in the safety of the dam because they prevent the downstream slope from sloughing, control the pore water pressures and the seepage flow. The drainage design is studied by several researchers and the outputs of these research were used in preparation of common design standards for drainage facilities which are USBR (1987, 2011a; b) and USACE (1994). The drainage facilities considered in this study are presented along with their design specifications herein.

2.1 Blanket Drain

Blanket drains are applied horizontally at the downstream part of the homogenous earth-fill dams. The typical cross-section of a blanket drain is given in Figure 2-1. Blanket drains are widely applied in small and moderate high earth-fill dams (Singh and Varshney 1995; USBR 1987), e.g. Lion Lake Dike (6.5 m high), Pishkun Dikes (13 m high), Dickinson Dam (14 m high). In addition to small dams, blanket drain has been widely applied in moderate high dams. The height of moderate high dams are usually between 20 m and 60 m high (Malekpour et al. 2012). The highest homogenous dam with a blanket drain is Vega Dam (50 m high) USBR (1987).

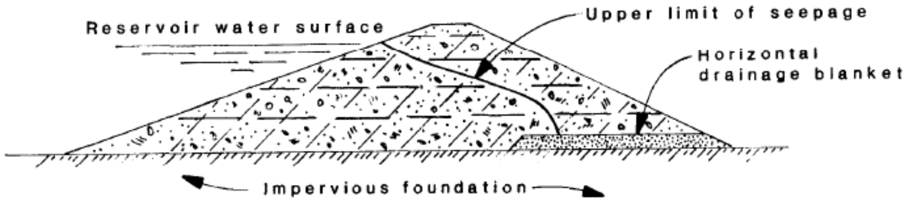

Figure 2-1: Typical cross-section of blanket drain in homogenous earth-fill dam (USBR 1987)

The geometry of the blanket drain affects the performance of the drain. The upstream end of the blanket drain is not recommended to extend to the centerline of the dam more than H+1.55 m in USBR (1987), where H is the height of the dam. In the same reference, the thickness of the blanket drain is recommended to be approximately 1 m. Additionally, Singh and Varshney (1995) stated that if the materials are assumed to be isotropic, the effective blanket drain length should be 0.12 times the reservoir head. Besides, Mishra and Singh (2005) recommended the blanket drain to be placed properly in order to avoid capillary rise on downstream slope.

2.2 Chimney Drain

Chimney drains may be applied on both homogenous and simple zoned type earth-fill dams. The simple zoned type earth-fill dams with chimney drain are commonly applied in practice. Some of the examples for chimney drain application are Sugar Pine Dam, Dry Falls Dam, San Justo Dike, Calamus Dam (USBR 1987), Ağcaşar Alatepe Dam, Aslantaş Dam and Keban Dam (Bilgi 1990). Chimney drains are placed at the downstream slope of the central core of the simple zoned earth-fill dams. In these types of dams, impervious core supports the chimney drain. Commonly, these drains end up with blanket drains to discharge water safely to the tailwater of the dam (Singh and Varshney 1995). A typical chimney drain illustration is provided in Figure 2-2.

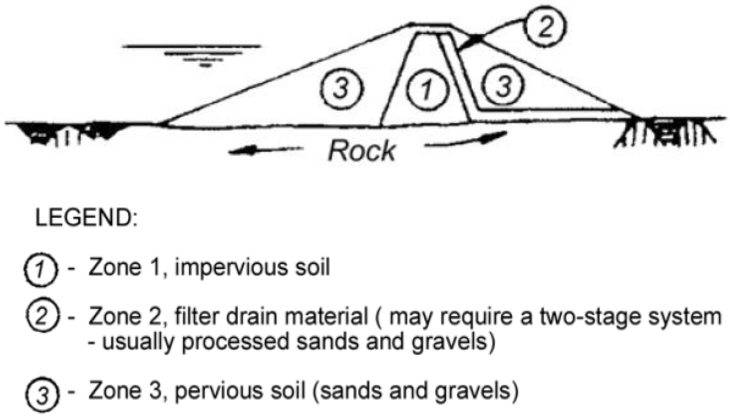

Figure 2-2: Typical cross-section of the chimney drain in a central core zoned type earth-fill dam (USBR 2012)

The orientation of the chimney drain may be either inclined or vertical. The inclined and vertical drains have their own advantages and disadvantages. Commonly, it is hard to construct an inclined drain; however, it has more advantages than the vertical ones. Inclined drain reduces the cracking of the core and decreases the length of the horizontal drains (FEMA 2011). Even if some defects occur in the core, chimney drain will supply an effective drainage (Golze 1977). This drain extends from the crest of the dam to its bottom and the phreatic surface of the seepage cannot reach to the downstream slope even if the embankment material is anisotropic (Montana Department of Natural Resources 2010; Singh and Varshney 1995) and the downstream part of the dam stays unsaturated. Therefore, pore water pressures decrease in the downstream zone. The recommended minimum thickness of the chimney drain is 1.5 m (FEMA 2011). The material property of the chimney drain is also very important. Cedergren (1967) and Taylor (1948) stated that the hydraulic conductivity of the chimney drain should be at least 16 to 25 times that of the clay core to have a sufficient drainage capacity. This can be satisfied by selecting an appropriate grain size distribution for the drainage facility.

2.3 Toe Drain

Toe drains are placed in the downstream part of the dam. Filling and compacting the soil layer by layer affect the seepage flow direction, which follows a horizontal path through the body, and toe drain can catch the flow lines easily (Sherard 1963). Toe drains have two different layouts. In the first layout, the drain is utilized with an additional internal drainage facility, such as the blanket or the chimney drain to discharge the collected water to the tailwater channel (FEMA 2011; USBR 1987). The typical cross-section of the toe drain placed below internal drainage facilities are given in Figure 2-3. This layout of the toe drain is commonly preferred when the internal drainage system is not sufficient (Cedergren 1967). The geometry of the toe drain with internal drainage systems is also important. This type of toe drain should have a side slope of 1V:1H for both upstream and downstream faces and its height should be in between 1 m and 4 m (Singh and Varshney 1995; USBR 1987). Also, collector pipes can be used in this type of toe drain. These pipes are commonly placed to ease the maintenance of the drain (Creager et al. 1945; FEMA 2011; Golze 1977). Also, pipes should have a sufficient capacity and should not be blocked by fine materials.

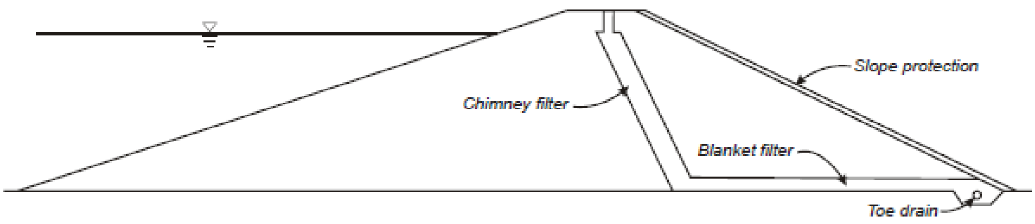

Figure 2-3: Typical cross-section of toe drain with internal drainage systems in homogenous earth-fill dam (FEMA 2011)

As a second possible layout, toe drains are used individually without an internal drainage facility. It can be used in both homogenous and simple zoned earth-fill dams (see Figure 2-4). However, it should be noted that these drains can only be used in homogeneous dams having a low or moderate height (Singh and Varshney 1995). The most important design parameter for this layout is the height of the toe drain. It should have a sufficient height to discharge the collected water. It is recommended by Creager et al. (1945) that the height of the drain should be 25% to 35% of the dam height. Singh and Varshney (1995) recommended toe drain height to be at least one fourth to one third of reservoir level. The design philosophy of the toe drain in homogenous dams is similar to that of the blanket drain. However, when the maintenance is considered, the toe drain is more advantageous than the blanket drain (Sherard 1963). Also, the construction of the toe drain is easier.

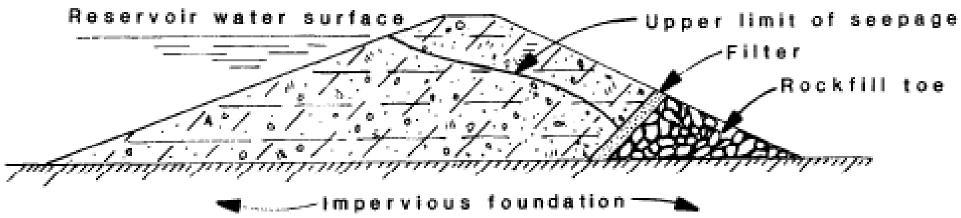

Figure 2-4: Typical cross-section of toe drain in homogenous earth-fill dam (USBR 1987)

CHAPTER 3

THE METHODOLOGY

Steady-State Seepage Analysis

Darcy's Law can be applied for modeling the seepage through saturated and unsaturated zones of an earth-fill dam (Richards 1931). It states that

$$q=-K*i \tag{3.1}$$

where q is the discharge per unit area, K is the hydraulic conductivity of soil and i is the hydraulic gradient.

The governing equation in two-dimension can be written as

$$\frac{\partial}{\partial x}\left(K_H \frac{\partial h_t}{\partial x}\right)+\frac{\partial}{\partial x}\left(K_V \frac{\partial h_t}{\partial y}\right)+Q=\frac{\partial \theta}{\partial t'} \tag{3.2}$$

where h_t is the total head, K_H and K_V are the hydraulic conductivities in horizontal and vertical directions, respectively, Q is applied boundary flux, θ is volumetric water content and t' represents time. This equation means that flow rates in x and y directions and the external applied flux are equal to change in the storage with respect to time (Geo-Slope Int Ltd. 2014a; Wang and Anderson 1982).

Under steady-state conditions the change in the storage is independent of time and the continuity requires the amount of flow entering and leaving an elemental volume is equal to each other. If the flow is considered as steady and the dam material is anisotropic Equation 3.2 reduces to:

$$\frac{\partial}{\partial \mathrm{x}}\left(\mathrm{K}_H \frac{\partial h_t}{\partial \mathrm{x}}\right)+\frac{\partial}{\partial \mathrm{x}}\left(\mathrm{K}_V \frac{\partial h_t}{\partial \mathrm{y}}\right)=0 \tag{3.3}$$

If the soil is considered as isotropic and homogeneous, *K* becomes independent of *x* and *y* directions. Therefore, Equation 3.3 reduces into:

$$\frac{\partial^2 h_t}{\partial x^2}+\frac{\partial^2 h_t}{\partial y^2}=0 \tag{3.4}$$

The equation above is called Laplace Equation. There are several methods to solve Equation 3.4, such as analytical, graphical, numerical and experimental methods. The numerical solution is easy to apply, fast, accurate, and economical.

Finite element method (FEM) is one of the most common numerical solution techniques. This technique divides the problem domain into elements with limited sizes and gives approximate solution for the nodes of the system. In FEM, any kind of complex geometry can be solved easily (P.S. Abhilasha and Balan 2014). The software SEEP/W (Geo-Slope Int Ltd 2015) utilizes FEM in order to solve the above governing equations in modeling the seepage through porous media.

SEEP/W Software

SEEP/W is a package of GeoStudio software which is released by GEO-SLOPE International (Geo-Slope Int Ltd. 2014a). SEEP/W can numerically model the seepage through embankments, confined and unconfined groundwater flow in isotropic and anisotropic porous media under steady-state and transient flow conditions using Darcy’s Law with saturated and unsaturated soil models. The numerical technique utilized is FEM.

In order to conduct seepage analyses, the geometry of the embankment is needed to be defined first. The geometry can be discretized either automatically or manually with a user defined size. The hydraulic gradients, pore water pressures, flow velocities, etc., are calculated in every nodal points. A smaller mesh size gives more sensitive results; however, this increases the computational load. In this study, the mesh size of the numerical models of the dams is globally selected as 1 m. Subsequently, the material properties are needed to be defined. In SEEP/W a saturated/unsaturated soil model can be utilized to model the embankment material. For this model, hydraulic conductivity function, anisotropy ratio and direction, and volumetric water content function should be entered. The volumetric water content is related with porosity of the soil. In steady-state analyses, there is no change in storage within the domain with time. Therefore, during design process of earth-fill dams under steady-state conditions, a volumetric water content function is not required. However, it is required for transient seepage analysis. There are well-known estimation methods for volumetric water content function in literature. SEEP/W is able to utilize grain size estimation methods which are Modified Kovács (1981), Fredlund and Xing (1994) and van Genuchten (1980) methods. In addition to these, it provides sample functions which create typical volumetric water content functions specific to material types. It also enables defining hydraulic conductivity functions with three methods. These are Fredlund and Xing (1994), Green and Corey (1971) and van Genuchten (1980). In this study, the closed form hydraulic conductivity function of van Genuchten (1980) method is utilized to estimate the unsaturated hydraulic conductivity. van Genuchten (1980) described the relative hydraulic conductivity value based on Mualem (1976) theory. The closed form analytical expression of hydraulic conductivity was derived by using an equation generated for soil water characteristic curve. A typical soil water characteristic curve for silty material is given in Figure 3-1.

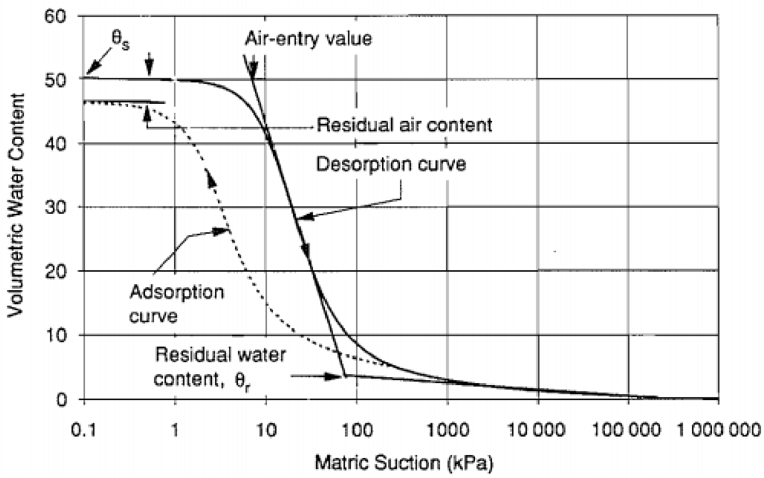

Figure 3-1: The typical soil water characteristic curve of silty soil (Fredlund and Xing 1994)

A relative hydraulic conductivity, K_r is determined by dividing unsaturated hydraulic conductivity, K, to the saturated hydraulic conductivity, K_s. The closed form analytical equation of the relative hydraulic conductivity is given in Equation 3.5 (Mualem, 1976).

$$K_r = \Theta^{1/2} \left[\int_0^{\Theta} \frac{1}{h_p(x)} dx / \int_0^{1} \frac{1}{h_p(x)} dx \right]^2 \qquad (3.5)$$

where h_p is pressure head and Θ is the dimensionless water content and its equation is provided in Equation 3.6.

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} \qquad (3.6)$$

in which, θ_s and θ_r represent saturated and residual water contents of the soil, respectively. The dimensionless water content may also be presented in terms of the pressure head and it is provided in Equation 3.7.

$$\Theta = \left[\frac{1}{1+(ah_p)^n} \right]^m \qquad (3.7)$$

Besides, the relative hydraulic conductivity can be defined as a function of Θ (Mualem, 1976).

$$K_r(\Theta) = \Theta^{1/2} \left[\frac{f(\Theta)}{f(1)} \right]^2 \qquad (3.8)$$

Using above equations, Equation 3.5 can be transformed into (van Gencuhten, 1980):

$$K_r(\Theta) = \Theta^{1/2} \left[1 - (1 - \Theta^{\frac{1}{m}})^m \right]^2 \qquad (3.9)$$

$$K_r(h) = \frac{\left\{ 1-(ah_p)^{n-1} \left[1+(ah_p)^n \right]^{-m} \right\}^2}{\left[1+(ah_p)^n \right]^{m/2}} \qquad (3.10)$$

where α, m and n are curve fitting parameters. The parameter m is calculated using the slope of the hydraulic conductivity function curve.

$$m = \begin{cases} 1-e^{(-0.8S_p)}, & 0<S_p<1 \\ 1-\frac{0.5755}{S_p}+\frac{0.1}{S_p^2}+\frac{0.025}{S_p^3}, & S_p>1 \end{cases} \qquad (3.11)$$

where S_p is the slope of the hydraulic conductivity function curve and it is defined with:

$$S_p = \frac{1}{(\theta_s - \theta_r)} \left| \frac{d\theta}{d(\log h_p)} \right| \tag{3.12}$$

The parameter n, *is* related *m* with the equation $n = 1/(1-m)$ and α is related with m with the following equation (van Genuchten 1980).

$$\alpha = \frac{1}{h_p} \left(2^{\frac{1}{m}} - 1 \right)^{(1-m)} \tag{3.13}$$

In van Genuchten (1980) method the hydraulic conductivity function is obtained using these equations. SEEP/W (Geo-Slope Int Ltd 2015) utilizes the saturated hydraulic conductivity, volumetric water content function, and the residual and saturated water contents to estimate the hydraulic conductivity function. These are obtained from the related literature. The software determines the hydraulic conductivity values at every nodal point according to pressure heads in an iterative manner.

The boundary conditions are also needed to solve the governing differential equation of the seepage. Boundary conditions are related with initial conditions and varied flow pattern of the system. Under steady-state flow conditions, the boundary conditions do not change with respect to time. In modeling the seepage through the dams considered, reservoir and tailwater levels are defined as a constant head boundary condition in this study. A seepage face may occur at the downstream side of the dam. In order to model this, a seepage face boundary condition, which allows flow through boundaries, is assigned to downstream slope. Additional information about modeling and solution techniques of SEEP/W is provided in reference manual, examples and tutorial videos (Geo-Slope Int Ltd 2015). The solution of a problem via SEEP/W yields the velocities and the gradients of the flow, pore water pressures, seepage rate through desired sections, equipotential lines, and flow paths.

CHAPTER 4

APPLICATION STUDY

In the application of this study, seepage analyses are performed for dams having blanket, chimney and two types of toe drains in order to determine the effectiveness of these facilities under steady-state flow conditions. The pore water pressures and seepage rate at the centerline of the dams are obtained and results are compared for various drain geometries and material properties. The embankment materials of the dams are assumed to be isotropic and homogenous. The foundations of the dams are assumed to be impervious. Throughout the study, the height of the dams are kept constant. In order to check any possible effects of the dam height on the seepage behavior of dams, three dams with different heights are considered in a preliminary analysis. Then, the geometries and material properties of the drainage facilities are determined and applied on a hypothetical dam cross-section. In order to investigate the effect of geometrical and material properties of drains on the seepage behavior of dams, the drainage properties are varied in different cases. The investigated alternatives are given in Figure 4-1.

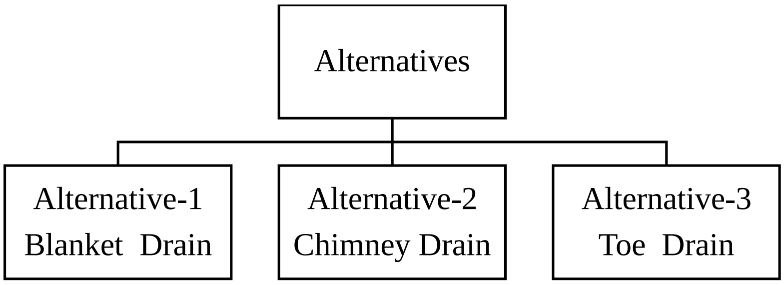

Figure 4-1: The alternatives considered in the study

The seepage rates of the considered cases are determined at the centerlines. Six nodal points are selected to investigate the spatial variation of the pore water pressure and to determine the effectiveness of drainage facilities in decreasing the pressures. The selected points and their coordinates are given in Figure 4-2 and Table 4-1, respectively.

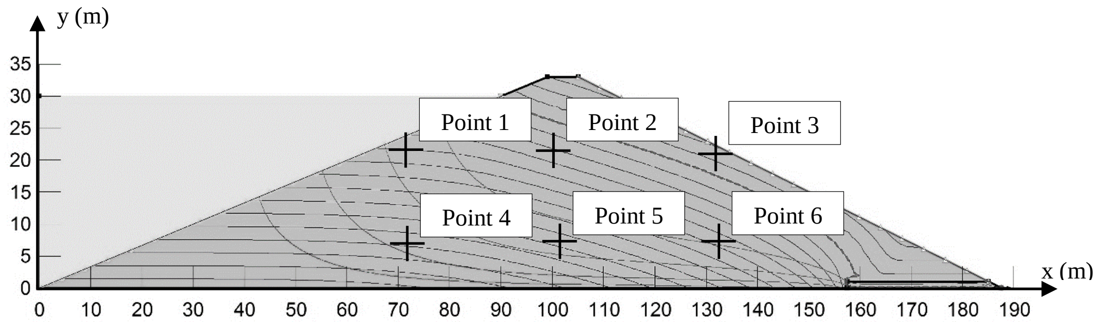

Figure 4-2: The defined points for determination of pore water pressure values

Table 4-1: Coordinates of the defined points

Point	x (m)	y (m)
1	73	20
2	101	20
3	131	20
4	73	6
5	101	6
6	131	6

4.1 The Determination of the Dam Cross-Section Properties

A hypothetical earth-fill dam geometry is selected from the study of Chahar (2004). The dam height is 33 m and the upstream and the downstream side slopes are 1V:3H and 1V:2.5H, respectively. The recommended slope for the upstream face vary between 1V:2H and 1V:4H, and whereas the same for the downstream face is in between 1V:2.5H and 1V:2H (USBR 1987). The side slopes of the selected dam are in between the recommended ranges. The dam crest width is 6 m and it is also in between the recommended limits which are 6 m and 12 m (Singh and Varshney 1995). Jansen (1988) also stated that the width of the crest is related with the requirements of the project and suggested a minimum width of 3 m and an average width which is 7.6 m. The base width of the selected dam is 187.50 m. This defined geometry is considered to be the geometries of a homogenous (see Figure 4-3 and Figure 4-5) and a simple zoned type dams (see Figure 4-4). For the simple zoned earth-fill dam, a central-symmetrical core is selected. The upstream and downstream slopes of the central core are determined to be 1V:0.5H (Bilgi 1990). The geometry of the core affects the geometry of the chimney drain and its effectiveness (FEMA 2011). The determination of the chimney drain geometry is explained in the relevant section.

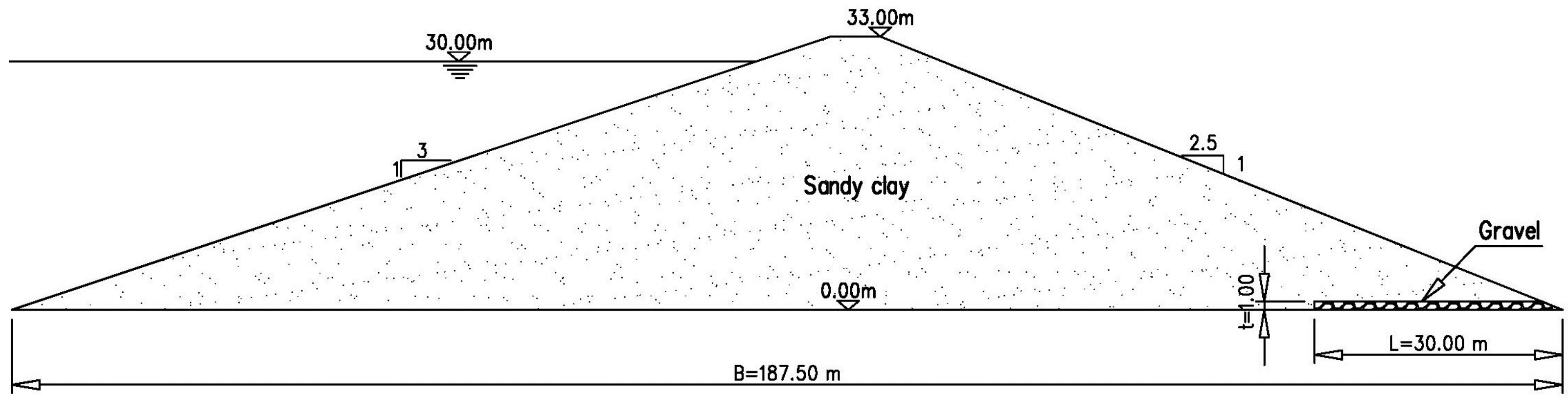

Figure 4-3: The homogenous earth-fill dam cross-section with a blanket drain

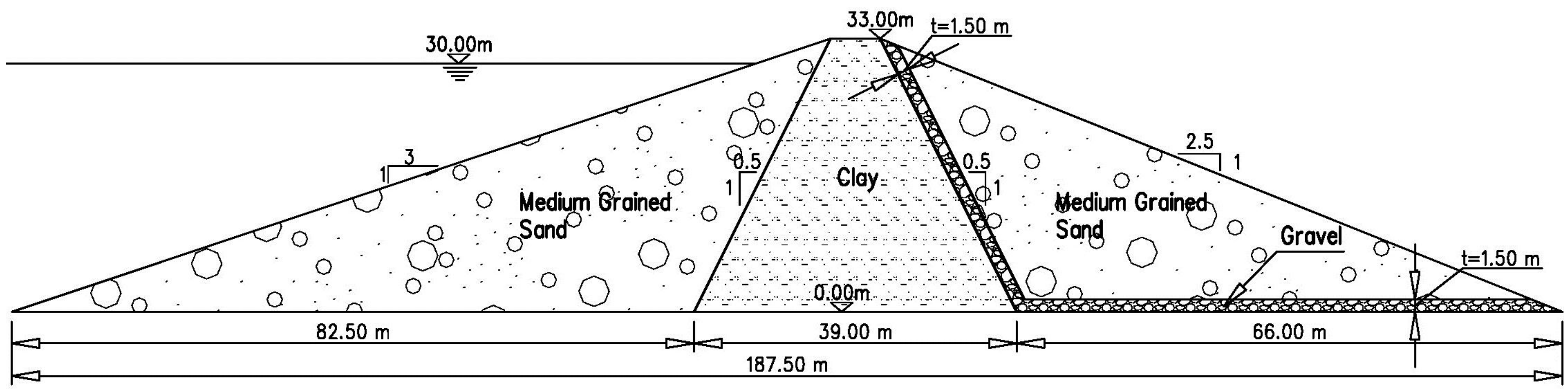

Figure 4-4: The simple zoned earth-fill dam cross-section with a chimney drain

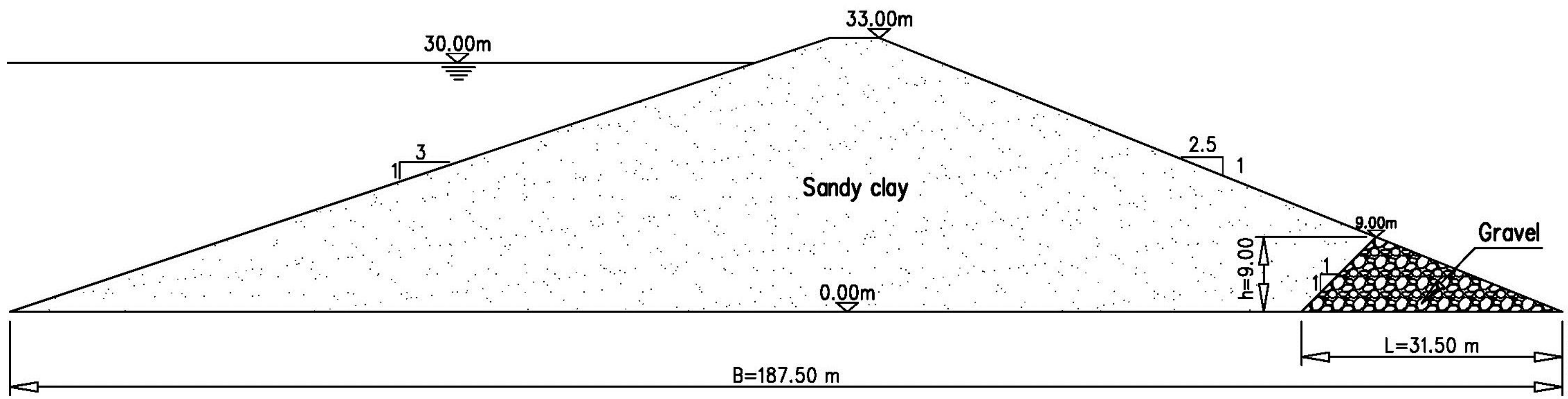

Figure 4-5: The homogenous earth-fill dam cross-section with a toe drain

4.2 The Determination of the Material Types

In the scope of this study, a hypothetical dam is selected for the analyses. In a real life application, the type of a dam and its materials are selected according to available materials in the close proximity of the construction area considering their quality (Sherard 1963). The materials of the considered dams are selected from commonly used materials in hydraulic engineering applications. For the homogenous layout, the dam itself has to satisfy its safety against seepage and piping. Therefore, the fill should be composed of sandy clay, sandy clay loams or fine materials (Singh and Varshney 1995). It is stated in the study of Singh and Varshney (1995) that clayey sandy gravels (GC), compacted clays of low plasticity (CL), silty sands (SM), poorly graded sands (SP) and compacted clays of high plasticity (CH) soils are also applicable in homogenous dams with internal drainage. The common characteristic of these materials is their low permeability which provides sufficient imperviousness in the dam body (Chahar 2004). For simple zoned earth-fill dams, the shell may be composed of more pervious material than core (Cedergren 1967). Singh and Varshney (1995) stated that clayey sandy gravels (GC), compacted clays of low plasticity (CL), poorly graded sands (SP), compacted clays of high plasticity (CH), might be used as core materials, whereas well graded sands (SW), well graded gravel (GW), silty sandy gravels (GM), poorly graded sands (SP) and poorly graded gravels (GP), might be applied as the pervious shell material at dams having an internal drainage facility. The determination of the materials of the embankment dams is also given by Bureau of Indian Standards (1988). It is stated that the most suitable material for the shell of a homogeneous dam is GC. Silty gravels may also be selected as the shell material; however, the use of poorly graded soils is not recommended. It should be noted that silty and organic materials are not preferred as dam and drain materials.

In the light of these information, the materials of the hypothetical homogeneous and simple zoned earth-fill dams considered in this study are determined. Sandy clay is selected as the homogenous dam fill material. Medium grained sand and clay are selected as the shell and core of the simple zoned earth-fill dam, respectively. Well graded gravel is determined as the material of the drainage facilities for all drain types as suggested in USBR (2011a; b). The hydraulic conductivity, residual and saturated water contents of each material are determined using the related literature. The hydraulic conductivity of sandy clay is stated to vary between 10^{-5} m/s and 10^{-9} m/s (Bowles 1996; Carsel and Parrish 1988; Terzaghi et al. 1996; USBR 2011a; West 1995). It is chosen as 10^{-8} m/s. The hydraulic conductivity of clay varies between 10^{-9} m/s and 10^{-12} m/s (Bowles 1996; Carter and Bentley 1991; Terzaghi et al. 1996; USBR 2011a; West 1995). It is taken as 10^{-9} m/s. The hydraulic conductivity of gravel generally varies between 10^{-1}m/s and 10^{-5} m/s (Bowles 1996; Das 2016; Malekpour et al. 2012; Terzaghi et al. 1996; West 1995). It is taken as 10^{-4} m/s. The hydraulic conductivity of medium grained sand is selected as $2x10^{-5}$ m/s from Tayfur et al. (2005). The saturated (θ_s) and the residual (θ_r) water contents of sandy clay and clay are determined from the study of Rawls et al. (1982), the same for medium grained sand these are determined from the study of Tayfur et al. (2005) and for gravel they are taken from the study of Malekpour et al. (2012). The properties of the materials used in the study are summerized in Table 4-2.

Table 4-2: The selected properties of the earth-fill dam materials

Material	***K*** **(m/s)**	**θ_s (cm³/cm³)**	**θ_r (cm³/cm³)**
Sandy clay (SC)	1.0×10^{-8}	0.4300	0.1090
Medium grained sand (MS)	2.0×10^{-5}	0.3640	0.0012
Clay (C)	1.0×10^{-9}	0.4750	0.0900
Gravel (GW)	1.0×10^{-4}	0.1000	0.0020

4.3 Preliminary Analyses

4.3.1 Effect of dam height on seepage behavior

In the application of this study, different drain types are applied to earth-fill dams which have the same height. However, any possible effects of the dam height on seepage behavior are needed to be investigated. To this end, a preliminary seepage analysis is conducted on both homogenous and simple zoned dams having three different heights are analyzed for seepage. A similar analysis was conducted previously by Çalamak et al. (2014). The same procedure applied in that study is adopted here in to investigate the effects of dam height on seepage.

The height of the dam selected for this study is 33 m. This height is increased and then decreased by 25% for homogeneous and simple zoned dam layouts in two separate cases. Then, steady-state seepage analyses are conducted for these cases. The seepage velocities at certain vertical planes and the seepage rates at the dam centerline are determined for all cases. Then, comparisons are made between the results of the cases. The selected vertical planes are presented in Figure 4-6.

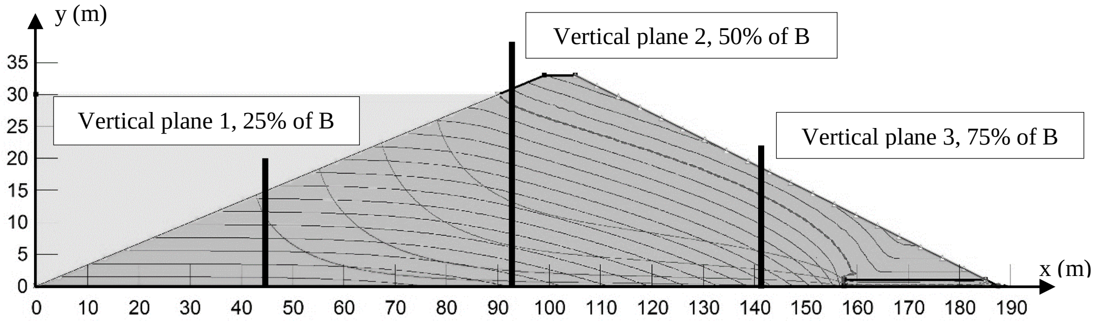

Figure 4-6: Selected vertical planes for different *x/B* values

The average velocity values along vertical planes are obtained and given in Figure 4-7 and Figure 4-8 in which *x* refers to the horizontal distance from the upstream end and *B* is the base width of the dam. As seen from the figures, seepage velocities have a similar magnitude and they do not change considerably with the change of the dam height.

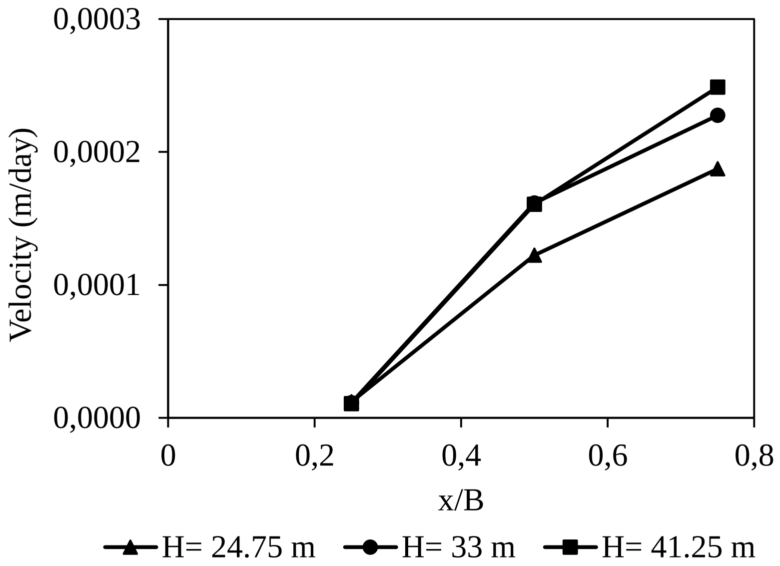

Figure 4-7: Average velocities with respect to *x/B* in the homogenous type earth-fill dam

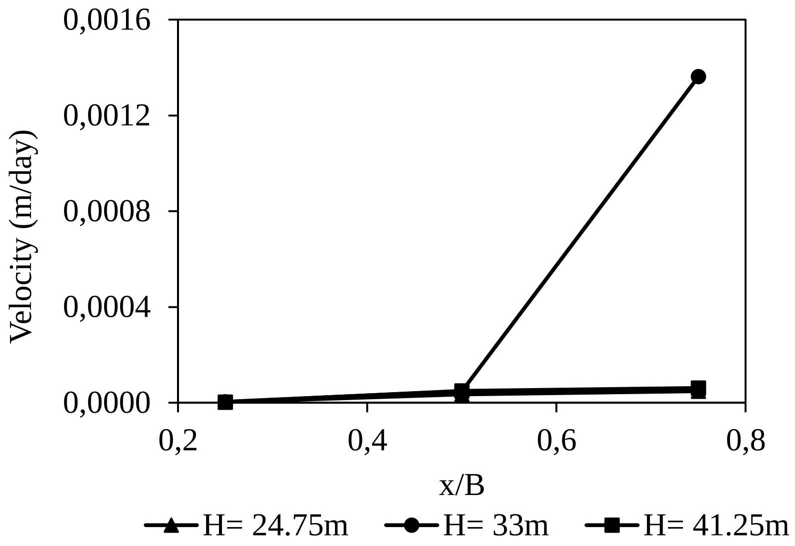

Figure 4-8: Average velocities with respect to *x/B* in the simple zoned type earth-fill dam

The seepage rates at the centerline are provided in Table 4-3. As seen from the table, seepage rates are closer to each other. When the dam height is increased, the reservoir level also increases and the average velocity through the vertical planes is almost not affected from these changes. It can be concluded that the seepage behavior of an embankment dam is related with its reservoir level and material properties. Therefore, throughout the study, analyses are conducted for constant height homogeneous and simple zoned dams.

Table 4-3: The seepage rates at the centerlines of the dams

Dam Type	**Seepage rate (l/h)**		
	H= 24.75 m	**H= 33 m**	**H= 41.25 m**
Homogenous	0.11	0.17	0.23
Simple Zoned	0.03	0.06	0.07

4.3.2 Effect of finite element mesh type and size on seepage behavior

SEEP/W allows user to determine mesh types and sizes. In this section of the study, the effects of mesh sizes and types on the seepage behavior are investigated. Analyses are conducted only for the earth-fill dam with the blanket drain. The length and the thickness of the blanket drain is taken as 30 m and 1 m, respectively. Firstly, the effects of the mesh type on pore water pressures and seepage rates at the centerline are investigated. Triangular mesh and automatic mesh options are separately selected and applied in two different cases with a global mesh size of 1 m. These cases are given in Figure 4-9 and Figure 4-10, respectively. Seepage rates at the centerline are found to be identical for the different types of mesh and the values are provided in Table 4-4. Pore water pressure values at predefined points are given in Table 4-5. The pore water pressures at predefined points also do not change. Only small variations are observed due to the different positions of the nodes. It is found that, the mesh type has not a distinct role on the seepage analysis results. Therefore, throughout the study, all analyses are conducted with automatic mesh type option, which is composed of triangles and quadrilaterals, of the software and a global mesh size of 1 m.

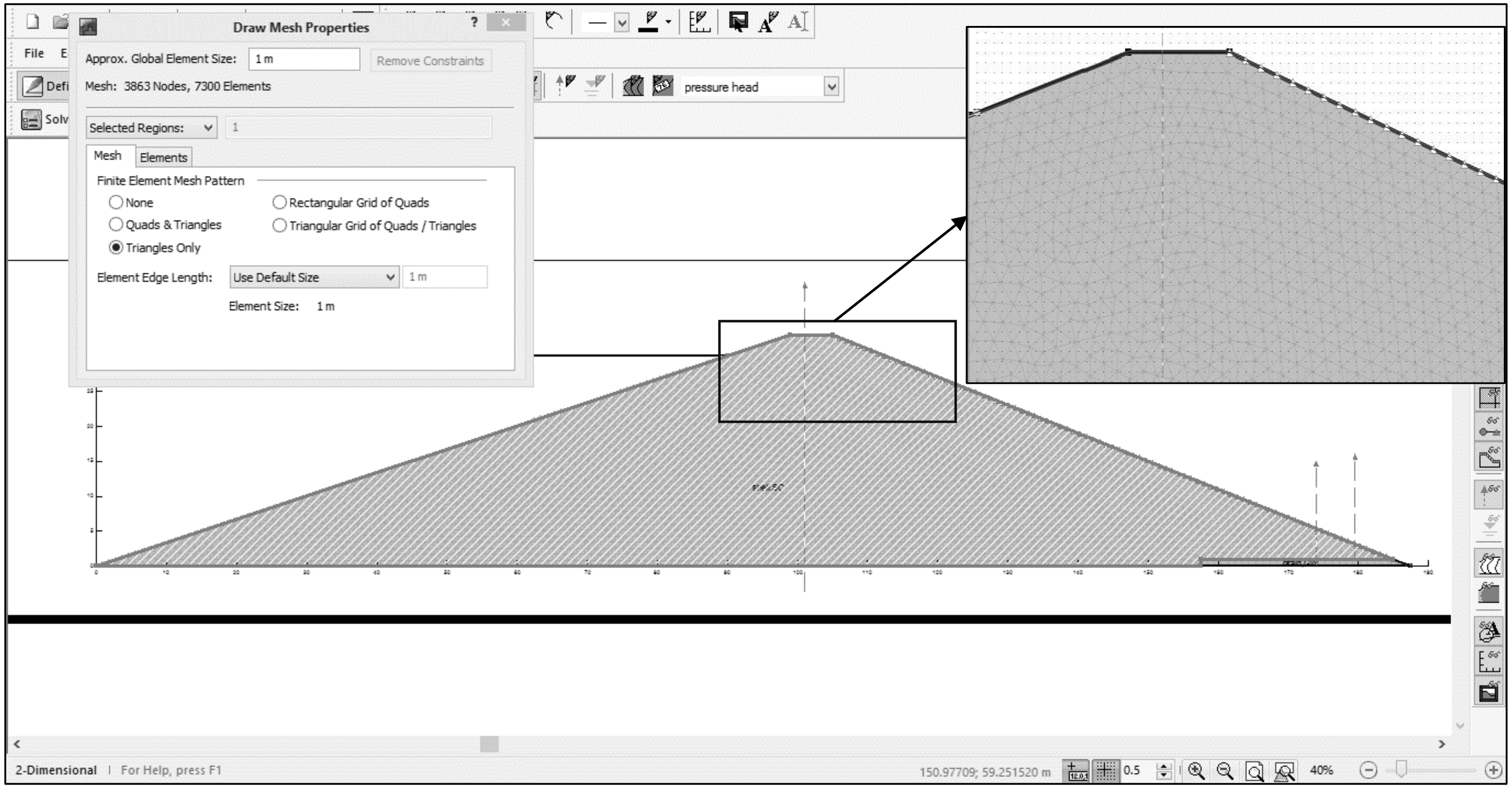

Figure 4-9: The model of triangular mesh type

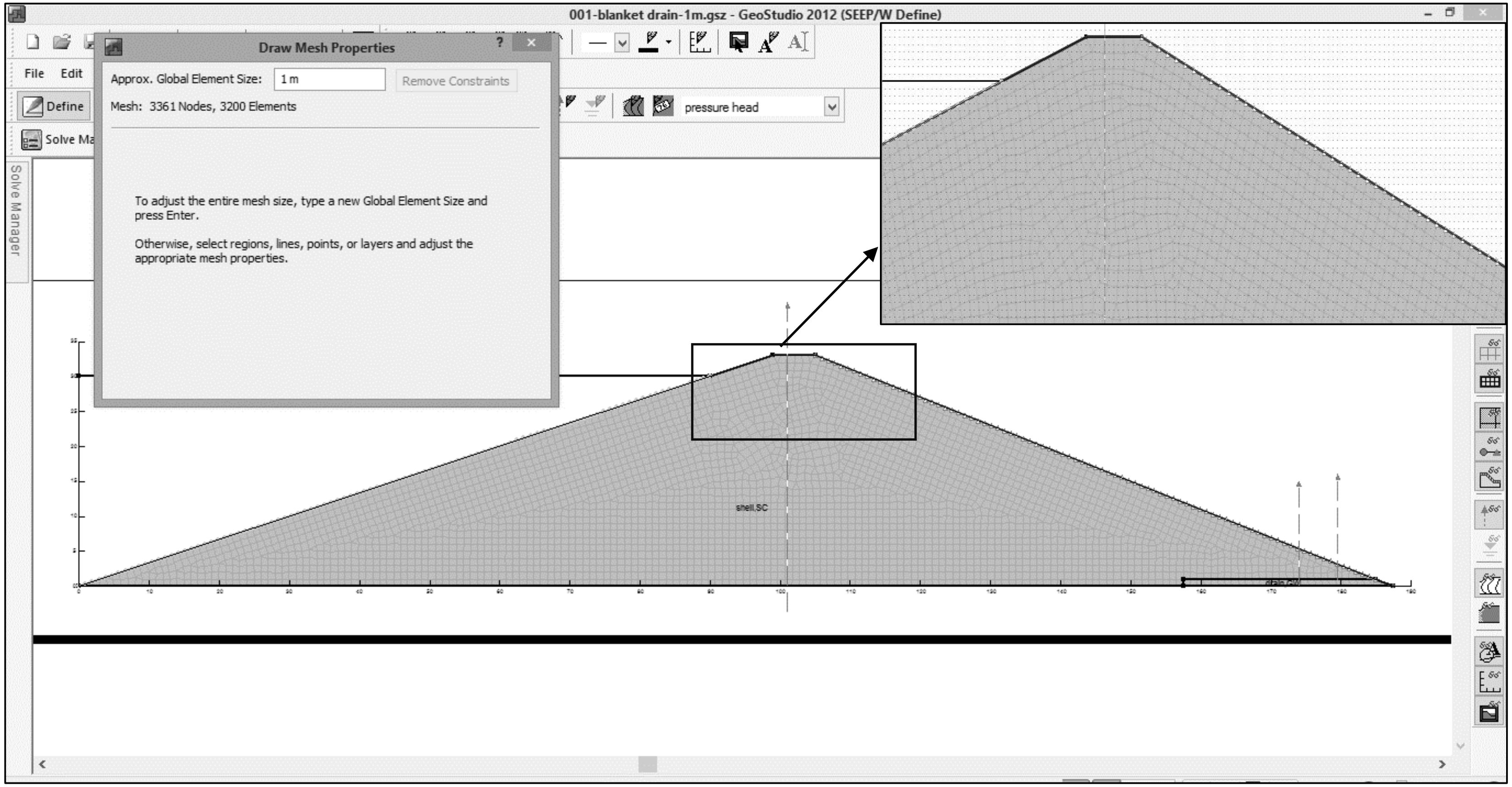

Figure 4-10: The model of automatic mesh type

Table 4-4: The seepage rates at the centerlines of the dams for triangular and automatic mesh types

	Mesh Type	
	Triangular	**Automatic**
Seepage rate (l/h)	0.203	0.203

Table 4-5: Pore water pressures at predefined points for triangular and automatic mesh types

Points	**Mesh Type**	
	Triangular	**Automatic**
1	87.72	92.18
2	51.14	48.27
3	-16.69	-22.78
4	223.62	223.83
5	184.34	183.89
6	108.07	106.94

Note: The pore water pressure values are in kPa.

In the scope of the study, the effects of mesh size on seepage analysis results are also assessed. More accurate results may be obtained from smaller mesh sizes of the problem domain. To investigate this, three different global mesh sizes, which are 0.5 m, 1 m and 2 m, are considered separately for the same earth-fill dam. The results of the seepage analysis are given in Table 4-6 and Table 4-7. According to the results, the seepage rate at the dam centerline and the pore water pressure distribution are not significantly affected from the mesh size. However, the smaller mesh size results in longer computation times. In this study, a global mesh size of 1 m is selected all of the analyses.

Table 4-6: The seepage rates at the centerlines of the dams of different mesh sizes

	Mesh Size		
	0.5 m	**1 m**	**1.5 m**
Seepage rate (l/h)	0.203	0.203	0.203

Table 4-7: Pore water pressures at predefined points of different mesh sizes

Points	**Mesh Size**		
	0.5 m	**1 m**	**2 m**
1	92.17	92.18	90.11
2	49.50	48.27	47.57
3	-22.97	-22.78	-24.78
4	223.84	223.83	223.80
5	184.02	183.89	184.22
6	116.48	106.94	106.45

Note: The pore water pressure values are in kPa.

4.4 Performance Assessment of Blanket Drain

The analyses are conducted for the blanket drain considering various alternatives for its length and thickness. The reference length and thickness of the drain are determined using design manuals and the related literature. The thickness of a blanket drain is recommended to be greater than or equal to 1 m in USBR (1987). Its length may be computed using the analytical equation of Chahar (2004). The maximum, minimum and optimum lengths of the blanket drain are related with the geometric parameters of the dam and the reservoir level. These relations are given in Equations 4.1, 4.2, and 4.3.

$$L_{min}{}^{*}=\frac{1e^2}{2e^2}\left\{0.3c+e+F_B{}^{*}(c+e)+T^{*}-\sqrt{[0.3c+e+F_B{}^{*}(c+e)+T^{*}]^2-e^2}\right\} \tag{4.1}$$

$$L_{max}{}^{*} = F_B{}^{*}(c+e)+T^{*}+\frac{1+e^2}{2e^2}\left[0.3c+e-\sqrt{(0.3c+e)^2-e^2}\right] \tag{4.2}$$

$$L^{*}=\frac{1+e^2}{2e^2}\left(0.3c+e+F_B{}^{*}(c+e)+T^{*}+\frac{e^2-1}{\sqrt{1+e^2}}d^{*}-\sqrt{\left[0.3c+e+F_B{}^{*}(c+e)+T^{*}-d^{*}\sqrt{1+e^2}\right]^2-e^2}\right) \tag{4.3}$$

Here, c and e represents the upstream and the downstream side slopes, respectively, F_B is the freeboard, T is the top width of the dam, L is the length of the drain and d represents the downstream slope cover. In Figure 4-11, defined geometric properties are presented. F_B*, T*, d*, L_{max}*, L_{min}* and L* are the non-dimensional parameters. They are obtained by dividing the nominal value of the parameter (indicated without an asterisk) to the water height, h_w.

For the application problem of this study, the values of h_w and d are 30 m and 5 m, respectively. When the Equations 4.1, 4.2, and 4.3 are applied, L_{min}, L_{max}, and L values are obtained as 14.6 m, 41.6 m and 30.4 m, respectively. The length and the thickness of the drain is selected as 30 m and 1 m, respectively. These values are assigned as reference dimensions. At first, the effect of the length on performance of the drain is investigated by keeping the thickness at its reference value, 1 m, and varying the length around its reference dimension, 30 m. The lengths of drain are varied between 20 m and 40 m with 5 m of increment. Then, the effect of the thickness on drain performance is investigated by keeping the length constant at its reference dimension, 30 m, and varying the thickness around its reference value. The thickness is varied between 0.5 m and 2.0 m with 0.5 m of increments. The investigated cases are given in Figure 4-12. The performance of the drain is assessed by investigating the changes in pore water pressures at predefined points (See Table 4-1 and Figure 4-2), the phreatic line position and the seepage flow at the centerline of the dam.

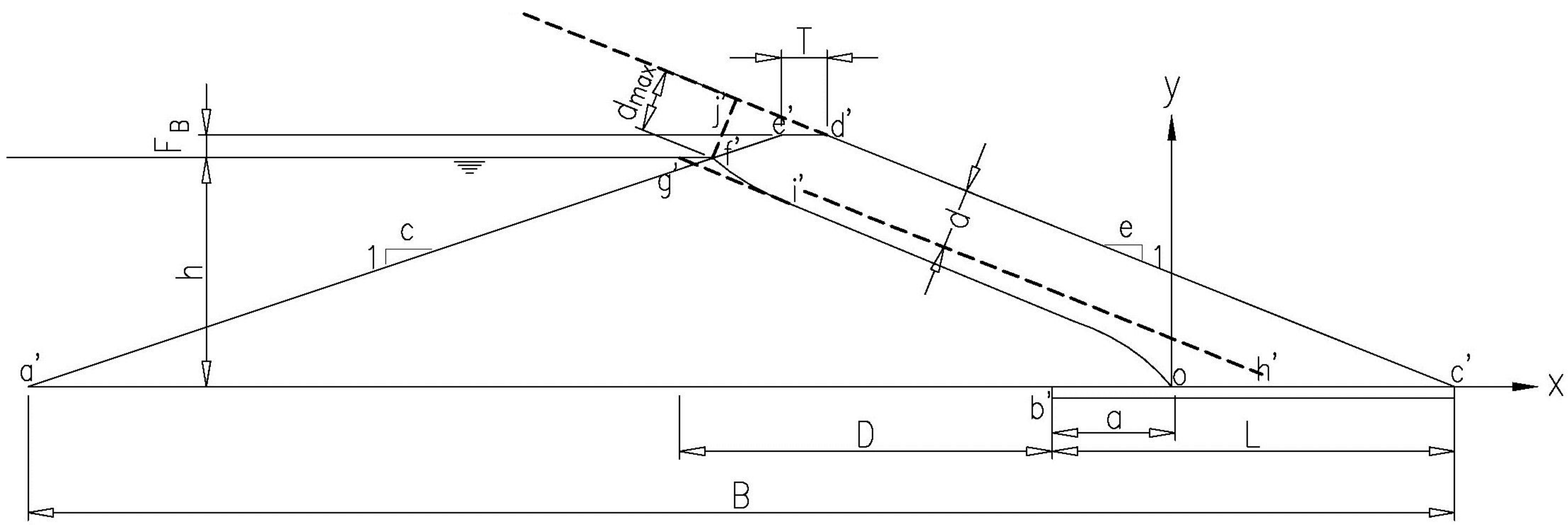

Figure 4-11: Definition sketch of the dam geometry (Chahar 2004)

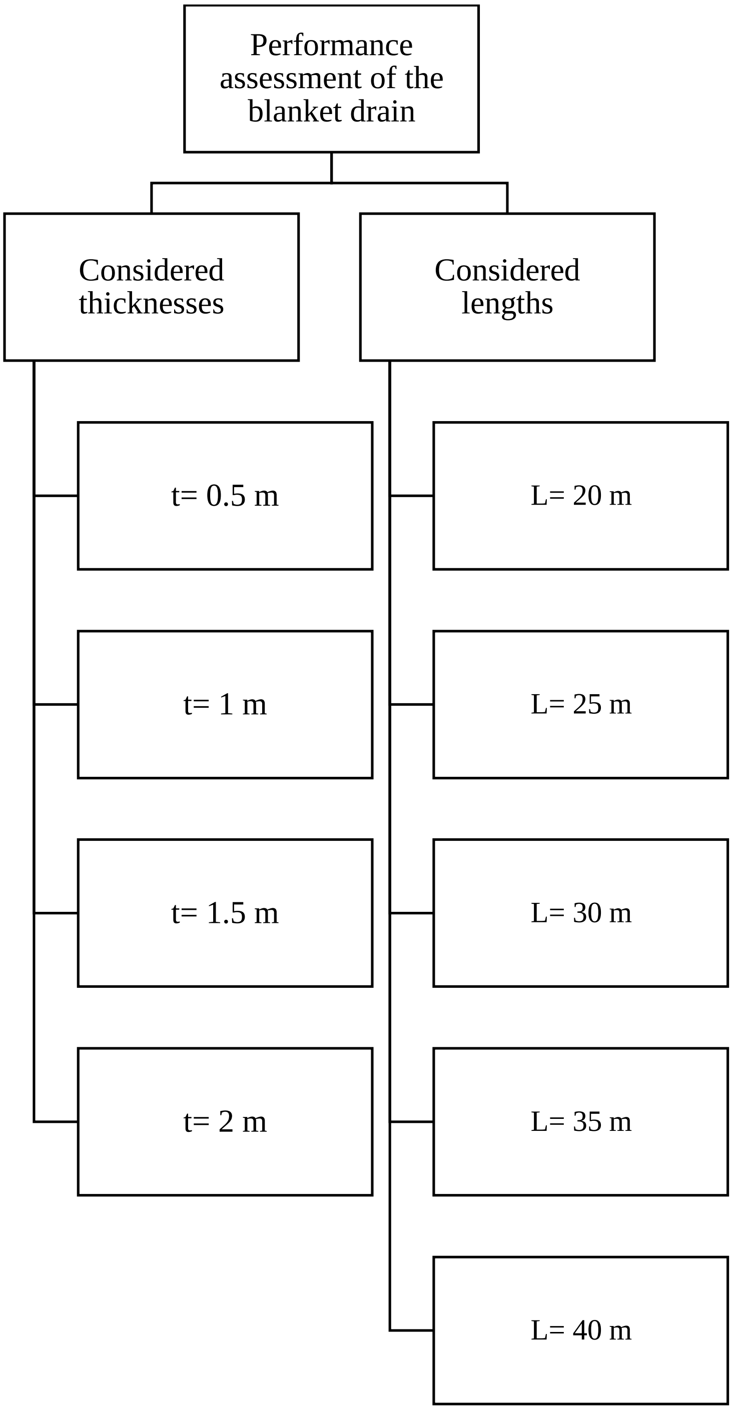

Figure 4-12: Investigated cases for the performance assessment of the blanket drain

4.4.1 The effects of the drain length

The effects of the drain length on the steady-state seepage behavior of the homogeneous dam are investigated by changing the length between 20 m and 40 m with 5 m increments. The changes in the phreatic line elevations and the pore water pressures at predefined points (see Figure 4-2) with respect to different drain lengths are shown in Figure 4-13 and Table 4-8, respectively. The graphical representation of the pore water variation is provided in Figure 4-14. Also, the variation of the seepage flow passing through the centerline with respect to the ratio of the drain length to the base width, *L/B*, are provided in Figure 4-15.

Table 4-8: Pore water pressures at predefined points for various lengths of the blanket drain.

Points	***L*= 20 m**	***L*= 25 m**	***L*= 30 m**	***L*= 35 m**	***L*= 40 m**
	***L/B*= 0.107**	***L/B*= 0.133**	***L/B*= 0.160**	***L/B*= 0.187**	***L/B*= 0.213**
1	92.6	92.4	92.2	91.9	91.6
2	63.9	55.7	48.3	50.0	43.0
3	-8.2	-14.7	-22.8	-31.7	-42.2
4	225.2	224.5	223.8	223.0	222.0
5	190.3	187.3	183.9	180.0	175.3
6	125.7	117.0	106.9	94.7	79.8

Note: The pore water pressure values are in kPa.

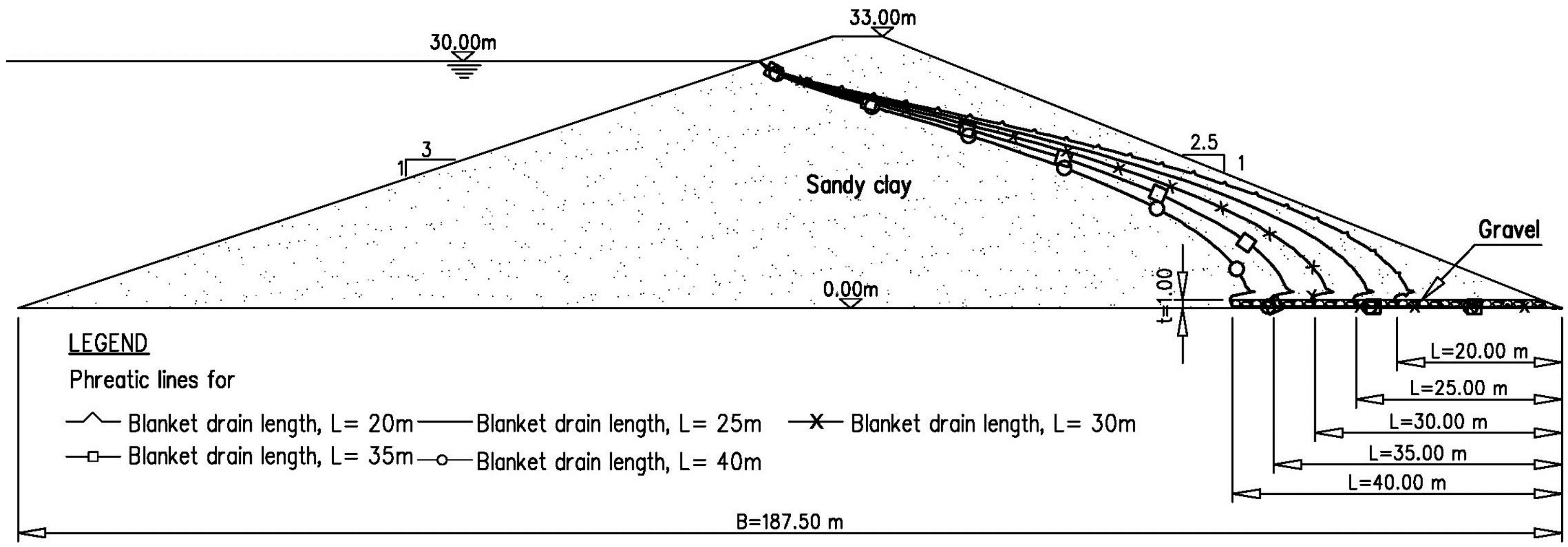

Figure 4-13: Phreatic lines for various lengths of the blanket drain

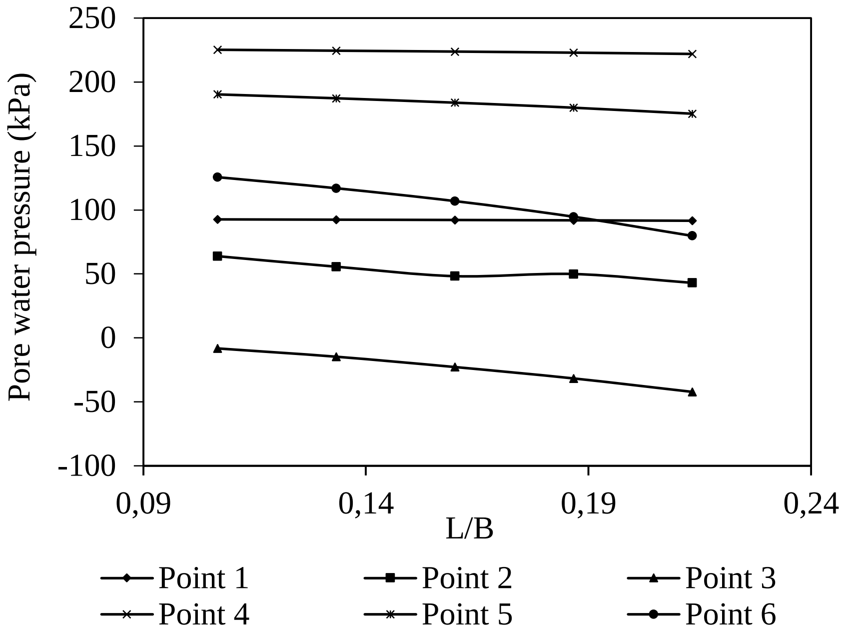

Figure 4-14: Pore water pressures at predefined points with respect to *L/B*

The results showed that the length of the blanket drain significantly affects the phreatic line and pore water pressures. The phreatic line meets with the drain within a shorter path (See Figure 4-13) when the length of the blanket drain is increased. It is clear that longer blanket drains are better in protecting the downstream slope from any negative effects of the seepage face since this option decreases the pore water pressures. The changes in the elevation of the phreatic line cause changes in the pore water pressure distribution. When the phreatic line meets with the drain in a shorter path, pore water pressures at specified points also decrease except for Points 1 and 4. These points are in the very upstream part of the dam and they are under the effect of upstream boundary condition. Also, they were observed to be in the saturated part of the dam body for all lengths of the drain. Therefore, they are not affected by the changes occurring at the downstream part of the phreatic surface. The seepage rate at the centerline is also affected with the change of the blanket drain length. When the length of the drain increases the seepage rate also increases (see Table 4-9 and Figure 4-15).

Table 4-9: Seepage rates at the centerline with respect to *L/B*.

	***L*= 20 m** *L/B*= **0.107**	***L*= 25 m** *L/B*= **0.133**	***L*= 30 m** *L/B*= **0.160**	***L*= 35 m** *L/B*= **0.187**	***L*= 40 m** *L/B*= **0.213**
Seepage rate (l/h)	0.181	0.191	0.203	0.216	0.231

In the scope of the study, the relationship between the seepage flows and *L/B* ratio is also investigated and the results are presented in Figure 4-15. It is found that the seepage flow is related with *L/B*, exponentially. The equation expressing the relationship is given below in Equation 4.4.

$$Q=288.68\exp\left(2.154\left(\frac{L}{B}\right)\right) \tag{4.4}$$

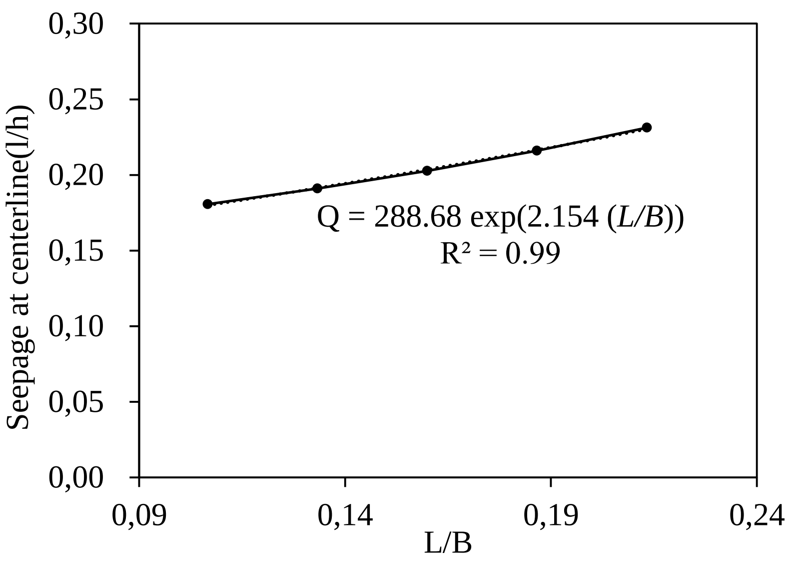

Figure 4-15: Graphical representation of seepage flows at the centerline with respect to *L/B*.

4.4.2 The effects of the drain thickness

The possible effects of the drain thickness variation on seepage behavior of the dam are also assessed. To this end, the thickness of the blanket drain is varied between 0.5 m and 2.0 m with 0.5 m of increments under a constant drain length of 30 m. The varying positions of the phreatic line and the pore water pressures for changing drain thicknesses are given in Figure 4-16 and Table 4-10, respectively. The graphical presentation of the pore water pressure variation is also given in Figure 4-16. The percent differences in pore water pressures computed using the pore water pressures obtained for the 1 m thick drain are given in Table 4-11. The results are given with respect to the thickness of the blanket drain, *t*, to the dam height, *H*, ratio (*t/H*). It is seen that when the thickness of blanket drain is increased, small changes are observed in the phreatic line elevations. It can be said that these changes do not considerably affect the performance of the drain. The pore water pressures change slightly in downstream part of the dam due to the changes in phreatic line. When the thickness is increased the pore water pressures slightly change only at Points 3 and 6 which are in the unsaturated zone. Malekpour et al. (2012) found similar results in an experimental study.

Table 4-10: Pore water pressures at specified points for various thickness values of the blanket drain.

Points	***t*= 0.5 m** ***t/H*= 0.015**	***t*= 1.0 m** ***t/H*= 0.030**	***t*= 1.5 m** ***t/H*= 0.045**	***t*= 2.0 m** ***t/H*= 0.061**
1	92.2	92.2	92.2	92.4
2	46.9	48.3	46.5	48.3
3	-22.7	-22.8	-23.1	-15.5
4	223.9	223.8	223.8	224.5
5	184.0	183.9	183.8	187.0
6	107.4	106.9	106.6	114.5

Note: The pore water pressure values are in kPa.

Table 4-11: The percent differences in pore water pressures for varied thickness values of the blanket drain

Points	*t*= 0.5 m *t/H*= 0.015	*t*= 1.0 m *t/H*= 0.030	*t*= 1.5 m *t/H*= 0.045	*t*= 2.0 m *t/H*= 0.061
1	0.03	Reference thickness	0.01	0.25
2	2.90		3.75	0.13
3	0.30		1.32	31.93
4	0.01		0.02	0.31
5	0.09		0.05	1.67
6	0.43		0.28	7.03

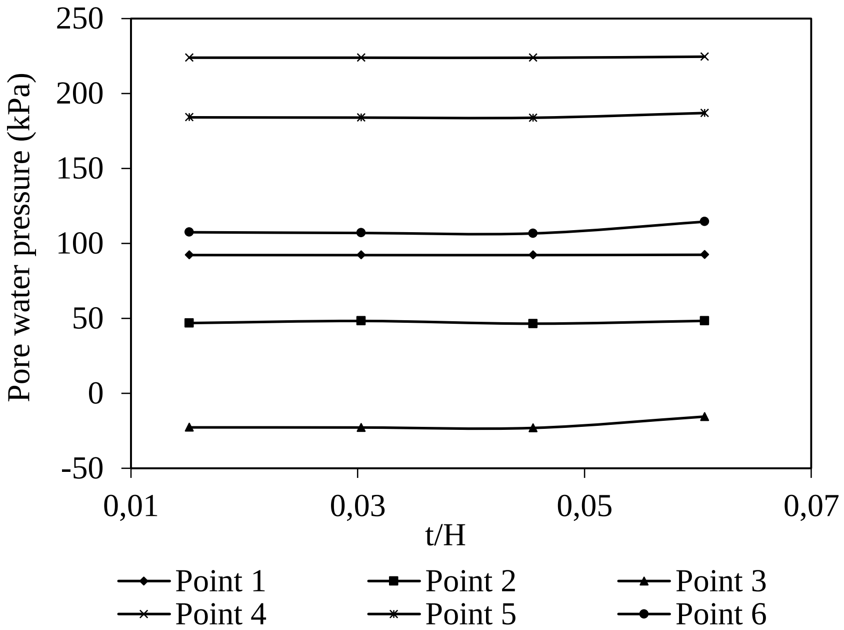

Figure 4-16: Pore water pressures at predefined points with respect to *t/H*

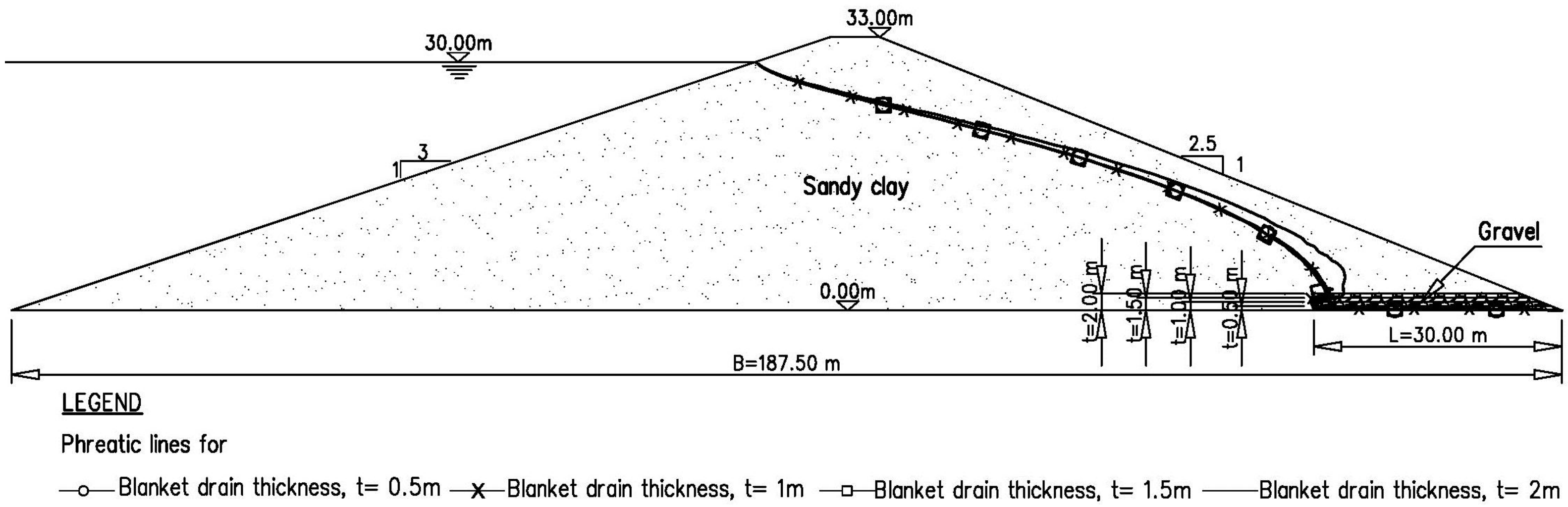

Figure 4-17: The phreatic lines for various thickness values of the blanket drain.

The seepage rates passing through the centerline of the dam for varied thicknesses of the blanket drain are shown in Table 4-12. It is seen that the flux also is not affected much by the variation of thickness of the blanket drain. Even the thickness of the drain is doubled, the rate is observed to decrease only by 5%. The same is also represented graphically in Figure 4-18. Similar discussions can be made by interpreting this figure.

Table 4-12: Seepage rates at the centerline with respect to *t/H*

	***t*= 0.5 m** ***t/H*= 0.015**	***t*= 1.0 m** ***t/H*= 0.030**	***t*= 1.5 m** ***t/H*= 0.045**	***t*= 2.0 m** ***t/H*= 0.061**
Seepage rate (l/h)	0.203	0.202	0.203	0.191

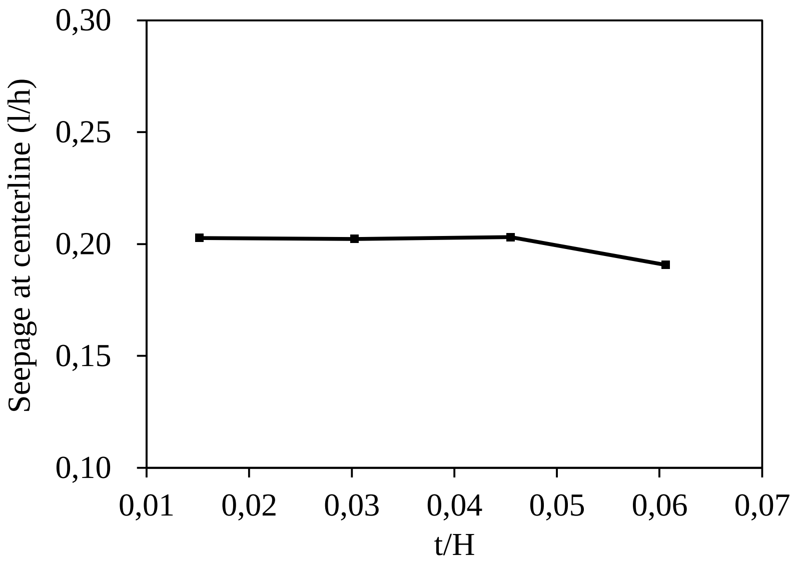

Figure 4-18: The graphical representation of seepage rates at centerline with respect to *t/H*

4.5 Performance Assessment of Chimney Drain

Thickness, material properties, upstream and downstream slopes of the core in a simple zoned earth-fill dam may affect the performance of a chimney drain. The possible effects of these elements are investigated herein. Analyses are conducted and compared with the reference geometry and material properties of the chimney drain, which are 1.5 m of thickness, 1H:2V downstream and upstream side slopes and a hydraulic conductivity of $1x10^{-4}$ m/s. To assess the performance of the drain, these properties are varied around their reference values.

At first, the thickness of the chimney drain is varied between 1 m and 2 m with 0.5 m increments. During this change, all other parameters are kept constant. Similar procedure is applied for the hydraulic conductivity and the slope of the drain. The change in the hydraulic conductivity is attributed to the variation in the grain size distribution of the chimney drain. The effects of the hydraulic conductivity are investigated by keeping the remaining properties constant. Finally, the slopes of the drain are changed for constant hydraulic conductivity and thickness. The investigated cases are introduced in Figure 4-19.

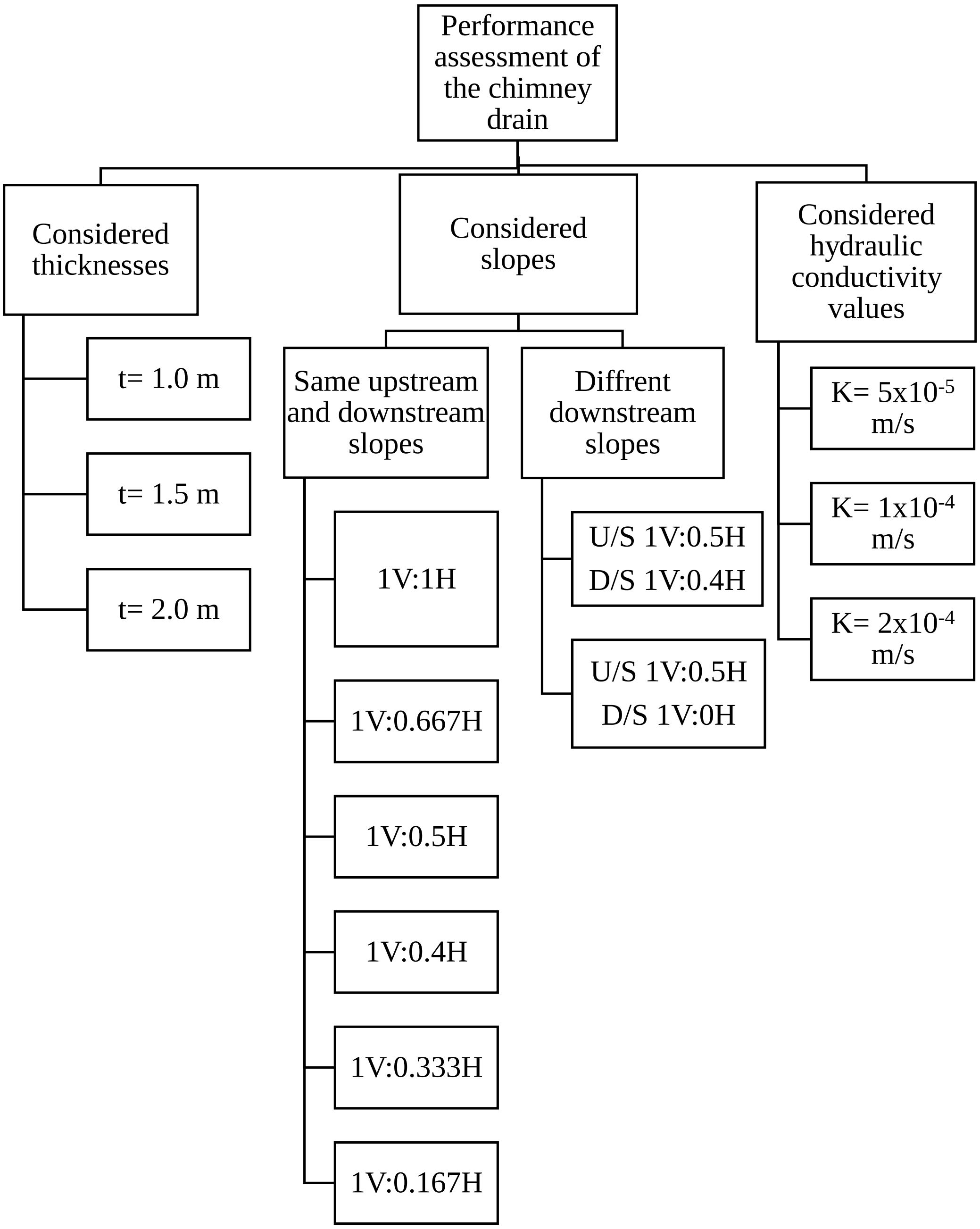

Figure 4-19: Investigated cases for the performance assessment of the chimney drain

4.5.1 The effects of the drain thickness

The effects of the chimney drain thickness on seepage flow, are investigated by examining the pore water pressures and the phreatic line position for various drain thicknesses. The hydraulic conductivity and the slopes of the core are kept constant at their reference values which are 1×10^{-4} m/s and 1V:2H, respectively, whereas the thickness of the drain is taken as 1 m, 1.5 m and 2.0 m. The phreatic line variation with respect to changing thickness is represented in Figure 4-20. It is seen that the elevations of the phreatic line change slightly. When the thickness of the blanket drain is smaller than the recommended thickness, t=1.5 m (FEMA 2011), which is the reference thickness in the study, it is seen that the phreatic line moves towards the downstream face of the dam. For the same case, the drainage facility is seen to be insufficient for draining the seepage flow. The results also showed that, when the drain thickness is 1.5 m or greater, the phreatic line follows the drain surface and the water is discharged safely.

The variation of pore water pressures are provided in Table 4-13 and Figure 4-21. In the upstream part at Points 1 and 4, where the shell of the dam is fully saturated, no changes are observed in the pressures. However, other points are seen to be affected by the changes in the phreatic surface elevation. When the thickness of chimney drain is varied, slight changes are observed in the pore water pressures. It is seen that when the thickness is increased, the pore water pressures decrease slightly. According to the results, it is more reasonable to select a thicker chimney drain to keep the phreatic line within the drain and protect the downstream part from sloughing. The percent differences in the pore water pressures at predefined points are also calculated and provided for different thickness of the drain to dam height ratios (*t/H)* in Table 4-14. Referring to the results, thicker drain gives lower percent difference values since the seepage flow is easily discharged with thicker drains.

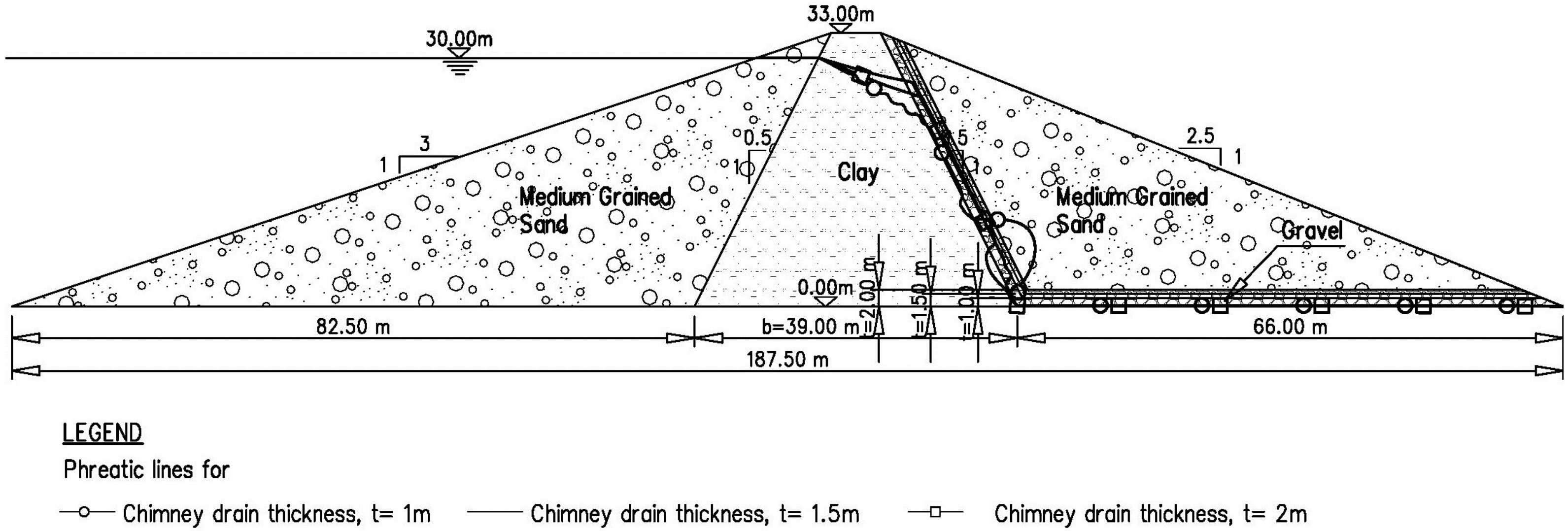

Figure 4-20: The phreatic lines for various thicknesses of the chimney drain

Table 4-13: The pore water pressures at predefined points for various thickness values of the chimney drain

Point	***t*= 1.0 m** ***t/H*= 0.030**	***t*= 1.5 m** ***t/H*= 0.045**	***t*= 2.0 m** ***t/H*= 0.061**
1	96.0	96.0	96.0
2	50.0	64.7	55.7
3	-139.4	-198.4	-197.3
4	235.7	235.7	235.7
5	162.0	179.5	163.0
6	-54.4	-53.2	-56.9

Note: The pore water pressure values are in kPa.

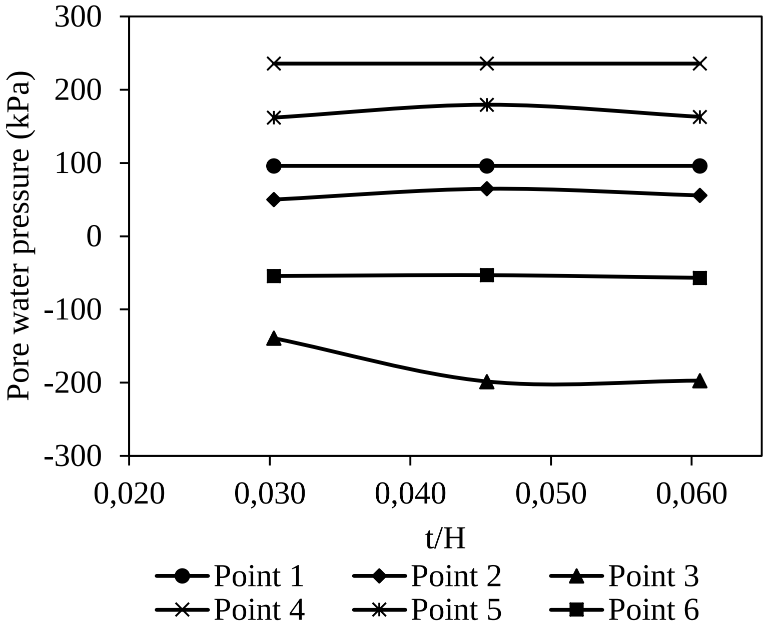

Figure 4-21: The variation of the pore water pressures with respect to *t/H*

Table 4-14: The percent differences in pore water pressures for different chimney drain thicknesses

Point	*t*= 1.0 m *t/H*= 0.030	*t*= 1.5 m *t/H*= 0.045	*t*= 2.0 m *t/H*= 0.061
1	0.00	Reference thickness	0.00
2	22.70		14.03
3	29.76		0.59
4	0.00		0.00
5	9.75		9.20
6	2.14		6.91

The seepage rates at the centerline for all varied thicknesses of chimney drain are given in Table 4-15 and Figure 4-22. The seepage rate does not vary in consistent manner. When the thickness is increased from 1 m to 1.5 m seepage rate decreases and differently when the thickness is increased from 1.5 m to 2 m seepage rate increases.

Table 4-15: Seepage rates at the centerline with respect to *t/H*

	t= 1 m ***t/H*= 0.030**	***t= 1.5 m*** ***t/H*= 0.045**	***t= 2 m*** ***t/H*= 0.061**
Seepage rate (l/h)	0.053	0.039	0.051

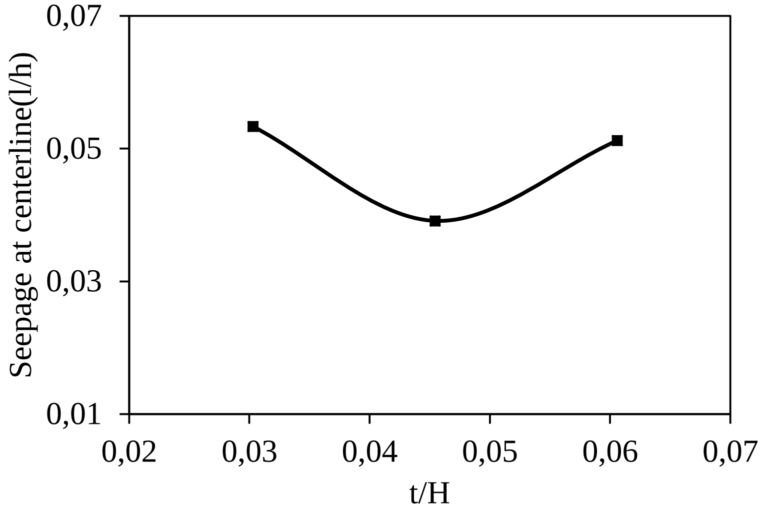

Figure 4-22: The graphical representation of seepage rates at centerline with respect to *t/H*

4.5.2 The effects of the impervious core slope

In the design of a simple zoned type earth-fill dam, the volume of the core is aimed to be minimized. It generally consists of impervious materials and these may not be available nearby the construction area. Therefore, considering the material constraints, the slope of the core can be varied. Jansen (1988) stated that the base width of the core should be at least 25% of the difference between reservoir and tailwater elevations. Considering this, the base width of the core should be larger than 7.5 m in the application of this study. The upstream side slope of the chimney drain is determined by the downstream slope of the core in a simple zoned earth-fill dam. In investigation of the effects of the side slopes of the drain on the seepage behavior, the reference slope of the drain, which is 1V:1H, is varied considering the information of existing earth-fill dams in Turkey provided in Bilgi (1990). The varied side slopes for the analyses are provided in Figure 4-19. The analyses are conducted for the same geometry and the boundary conditions of the dam. The phreatic lines obtained for various drain slopes are shown in Figure 4-23 to Figure 4-28. The pore water pressures at predefined points for varied drain slopes are given in Table

4-16. The pore water pressures with respect to base width of the core to the base width of the dam (*b/B*) are provided in Figure 4-29. The results showed that the upstream part of the dam is kept saturated and the elevations of the phreatic surface do not change for all cases. The results also showed that there are almost no changes in the pore water pressures at Points 1 and 4. However, Points 2 and 5 are observed to be the most affected points from the changes of core slopes. When the side slopes of the core are relatively milder, the phreatic line of the seepage does not reach to the inclined part of the drain, it follows a steeper path inside the core and leaves the dam body from the horizontal part of the chimney drain. This is observed at the dams having core slopes of 1V:1H and 1V:0.667H. The pore water pressures through the dam body are smaller for these alternatives except for the unsaturated zone of the dam. Therefore, it can be concluded that the volume of the core zone can be minimized in simple zoned earth-fill dams having chimney drains.

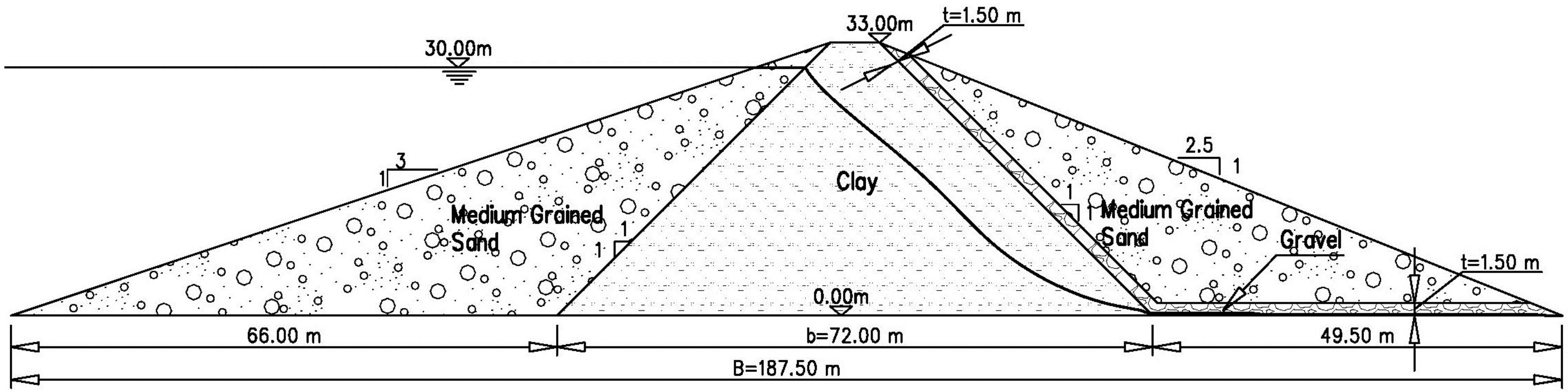

Figure 4-23: The phreatic surface for core slopes 1V:1H

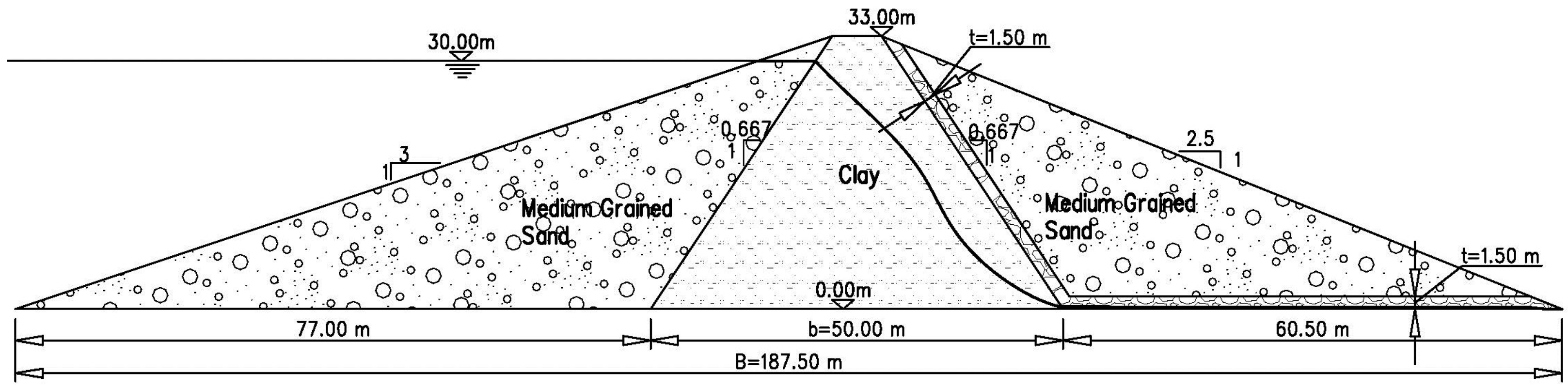

Figure 4-24: The phreatic surface for core slopes 1V:0.667H

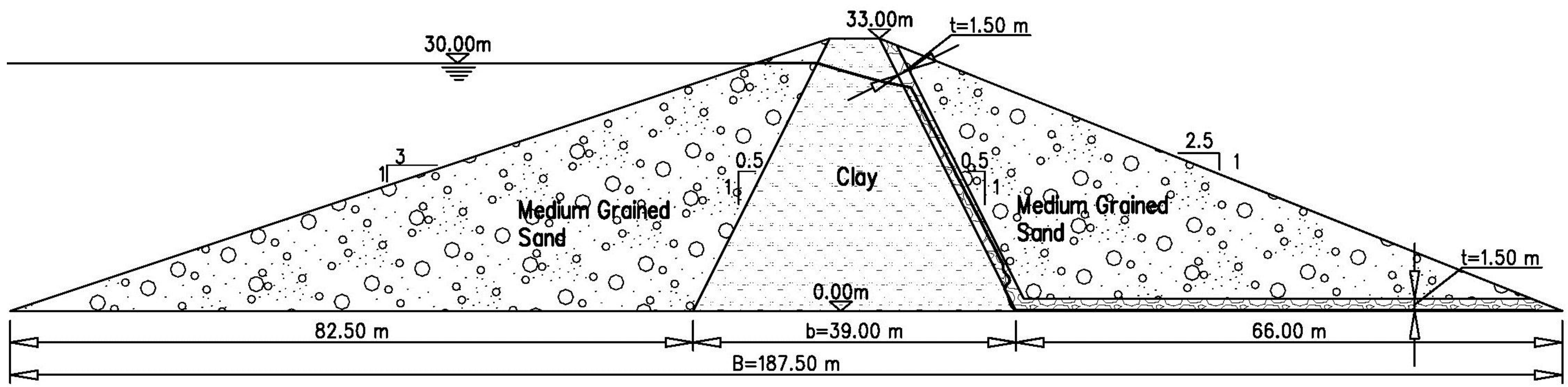

Figure 4-25: The phreatic surface for core slopes 1V: 0.5H

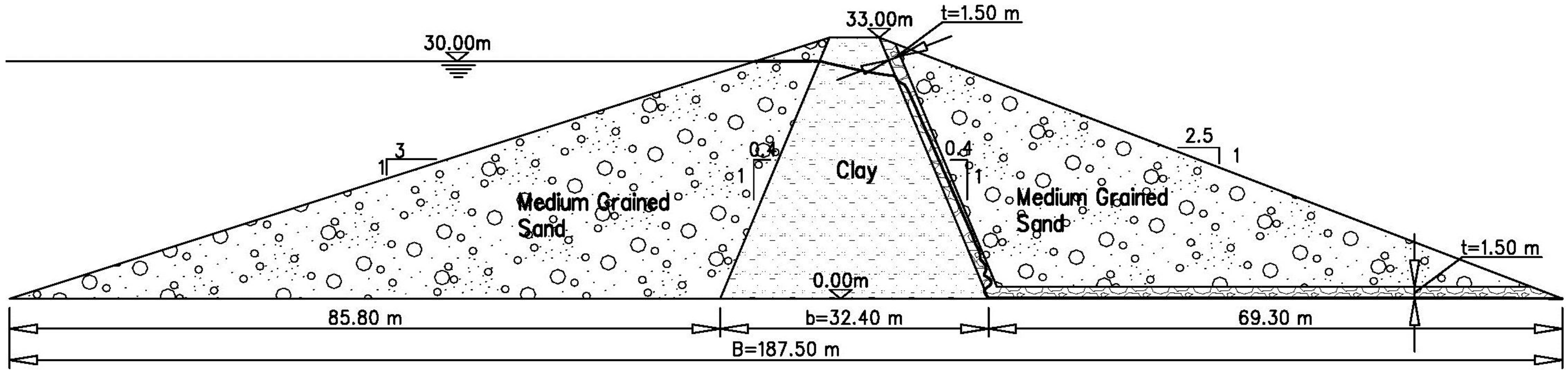

Figure 4-26: The phreatic surface core slopes 1V:0.4H

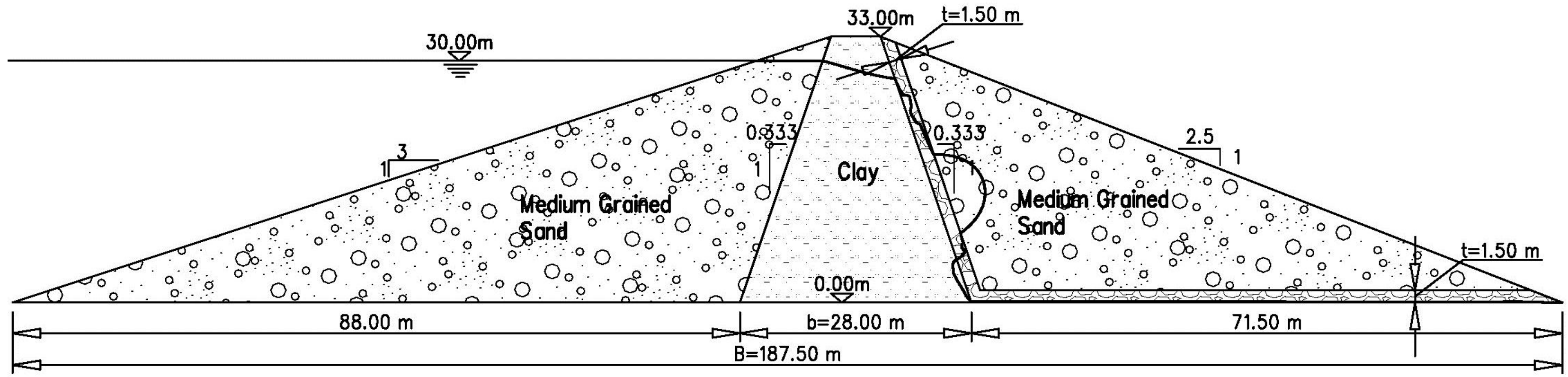

Figure 4-27: The phreatic surface for core slopes 1V:0.333H

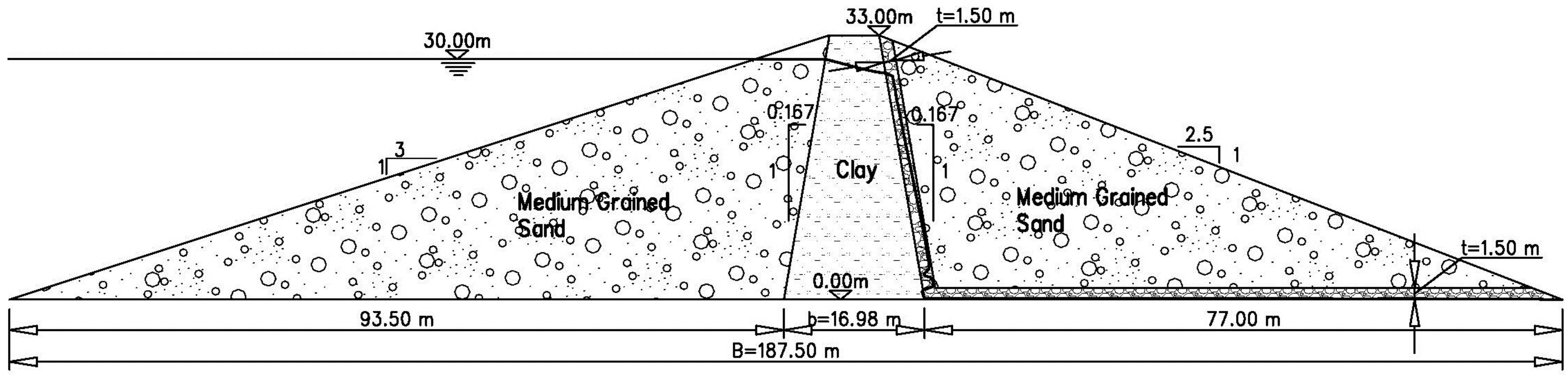

Figure 4-28: The phreatic surface for core slopes 1V: 0.167H

Table 4-16: The pore water pressures for various core and drain slopes at predefined points

Point	*1V:1H* b/B= 0.384	*1V:0.667H* b/B= 0.267	*1V:0.5H* b/B= 0.208	*1V :0.4H* b/B= 0.173	*1V :0.333H* b/B= *0.149*	*1V :0.167H* b/B= *0.091*
1	96.0	96.0	96.0	96.0	96.0	96.0
2	25.6	31.5	64.7	72.7	65.7	69.8
3	-197.4	-194.7	-198.4	-198.9	-159.1	-199.1
4	237.8	236.4	235.7	235.5	235.3	235.1
5	143.8	139.1	179.5	178.9	164.4	185.9
6	-43.0	-51.7	-53.2	-52.6	-52.3	-52.6

Note: The pore water pressure values are in kPa.

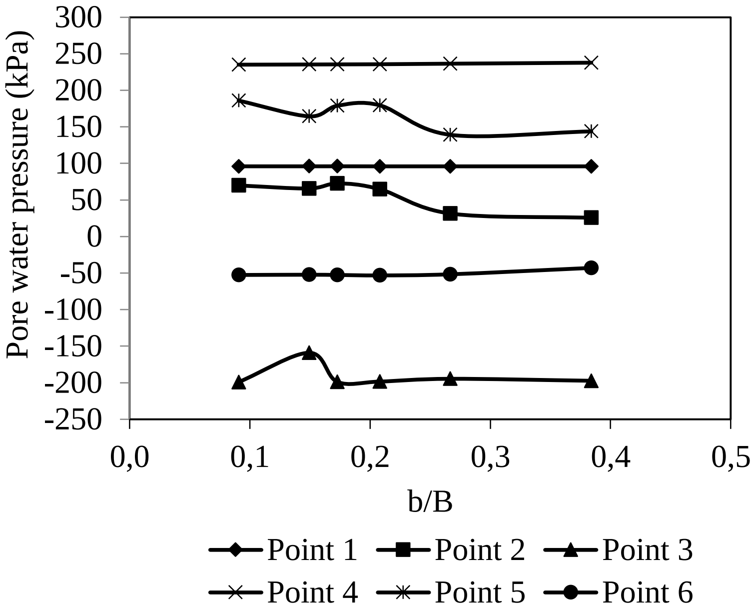

Figure 4-29: The graphical representation of pore water pressures with respect to *b/B*

Seepage flows at the centerline of the dam are given in Table 4-17 and Figure 4-30. According to the results, the variations of the seepage are not consistent.

The seepage rates are seen to be very small due to the presence of impervious core.

Table 4-17: Seepage rates at the centerline with respect to *b/B*

	1V:1H	***1V:0.667H***	***1V:0.5H***	***1V :0.4H***	***1V :0.333H***	***1V :0.167H***
	b/B= **0.384**	***b/B=*** **0.267**	***b/B=*** **0.208**	***b/B=*** **0.173**	***b/B=*** ***0.149***	***b/B=*** ***0.091***
Seepage rate (l/h)	0.058	0.069	0.039	0.040	0.058	0.057

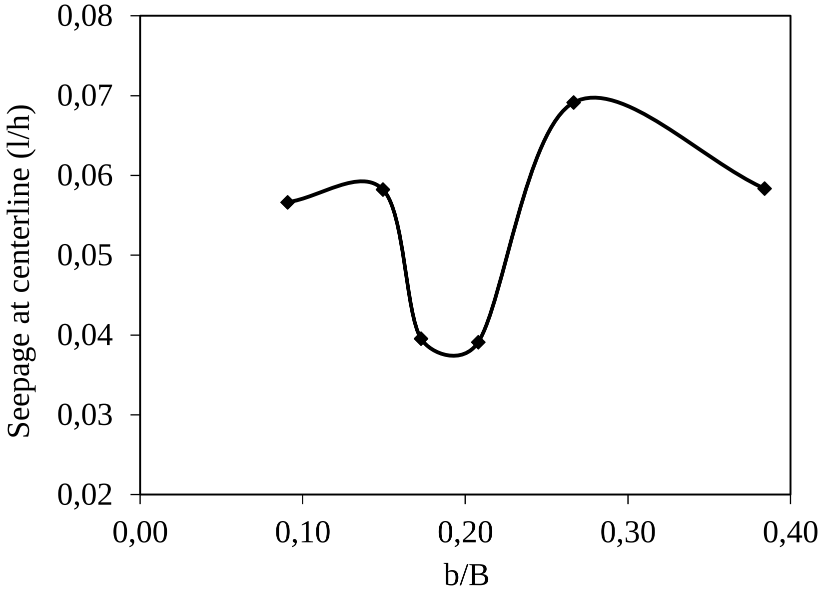

Figure 4-30: The graphical representation of seepage rates at the centerline with respect to *b/B*

A different set of analyses are conducted for asymmetrical upstream and downstream slopes of the core. In these analyses, the upstream slope of the core is kept constant at 1V:0.5H, whereas the downstream slope is taken as 1V:0.4H and 1V:0H. The obtained phreatic surfaces and the pore water pressures for varied drain slopes are provided in Figure 4-32, Figure 4-33 and Table 4-18.

The phreatic line of the dam which has a downstream core slope of 1V:0.4H directly meets the horizontal part of the drain without meeting inclined part of the drain as shown in Figure 4-32. The percent differences of pore water pressures at predefined points are given in Table 4-19. It is seen that at Points 2 and 5 the differences are higher. When the downstream slope of the core is 1V:0H, the phreatic line does not descend and meets with the chimney drain due to the narrower core as shown in Figure 4-33. Therefore, the percent difference of pore water pressure at Point 2 is less than that is obtained for the case having the downstream core slope of 1V:0.4H.

Table 4-18: The pore water pressures at specified points for varied downstream slopes with constant upstream slope

Point	***U/S 1V:0.5H*** ***D/S 1V :0.5H*** ***b/B*= 0.208**	***U/S 1V:0.5H*** ***D/S 1V :0.4H*** ***b/B*= 0.190**	***U/S 1V:0.5H*** ***D/S : 1V:0H*** ***b/B*= 0.131**
1	96.0	96.0	96.0
2	64.7	11.7	48.1
3	-198.4	-195.3	-185.3
4	235.7	235.7	235.7
5	179.5	104.8	80.4
6	-53.2	-49.0	-47.2

Note: The pore water pressure values are in kPa.

Table 4-19: The percent differences in pore water pressures for varied downstream slopes of the core

Point	***U/S 1V:0.5H*** ***D/S 1V :0.5H*** ***b/B*= 0.208**	***U/S 1V:0.5H*** ***D/S 1V :0.4H*** ***b/B*= 0.190**	***U/S 1V:0.5H*** ***D/S : 1V:0H*** ***b/B*= 0.131**
1		0.00	0.00
2		81.94	25.67
3	Reference	1.58	6.61
4	D/S slope	0.00	0.00
5		41.65	55.22
6		7.87	11.25

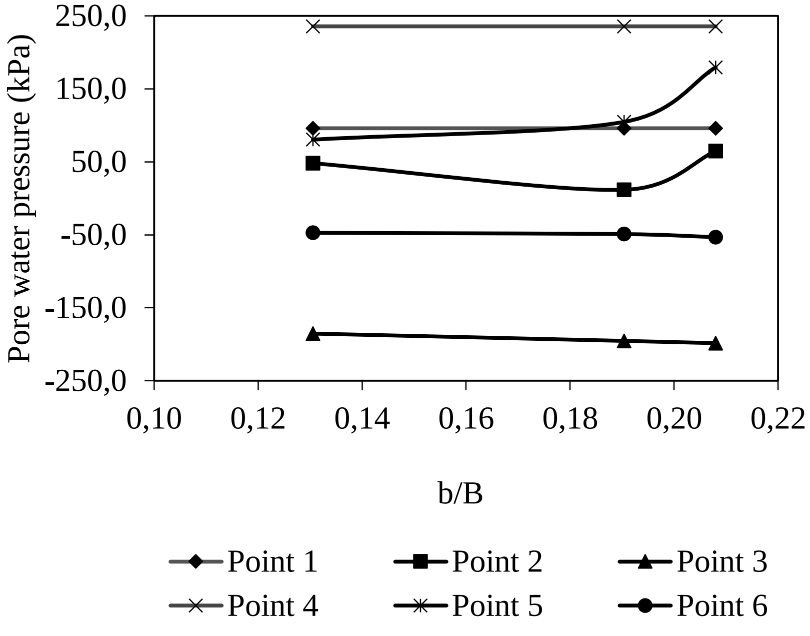

Figure 4-31: The graphical representation of pore water pressures for varied downstream slopes of core with respect to *b/B*

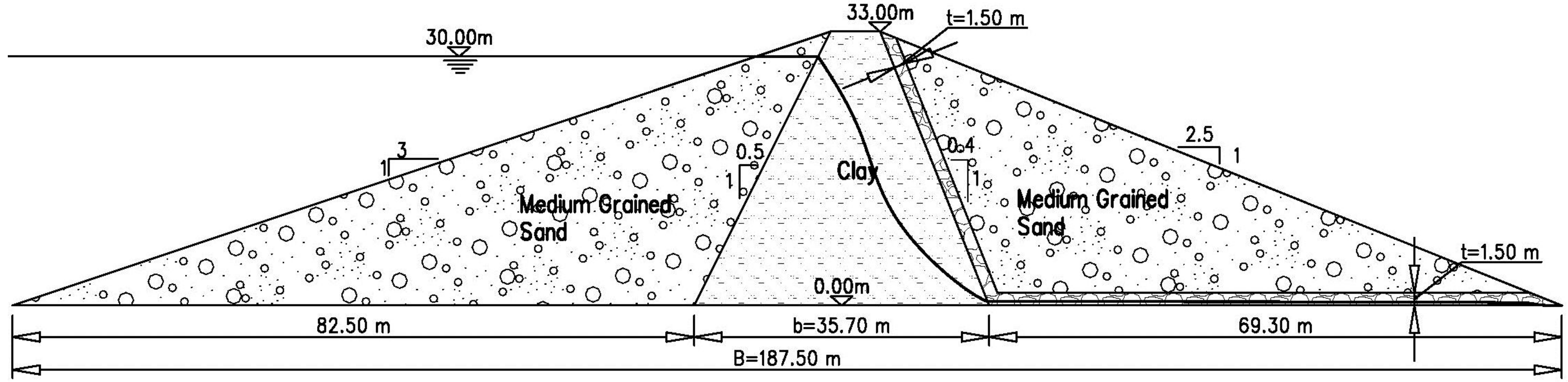

Figure 4-32: The phreatic surface when upstream core slope is 1V: 0.5H and downstream core slope is 1V:0.4H

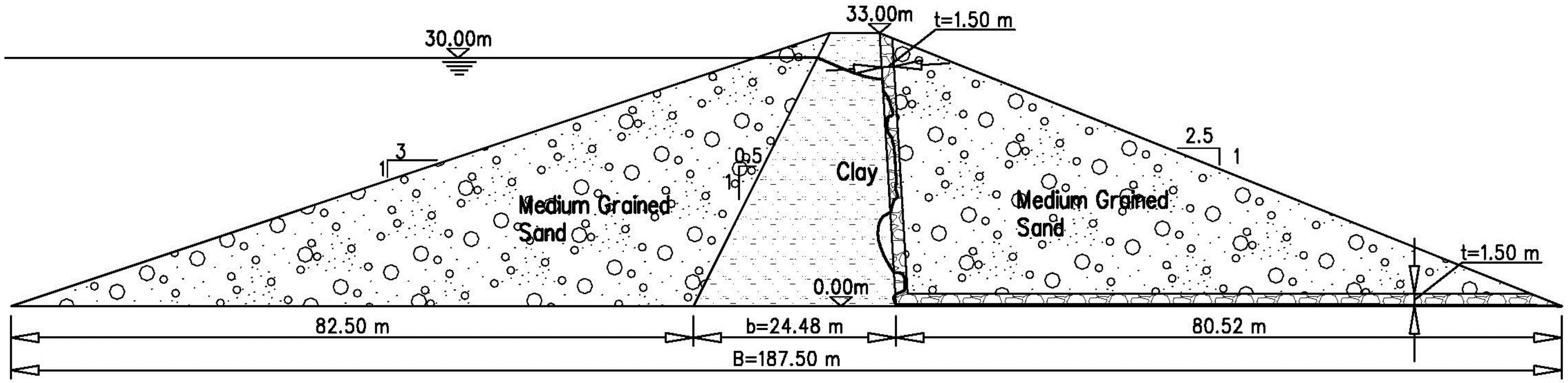

Figure 4-33: The phreatic surface when upstream core slope is 1V: 0.5H and downstream core slope is vertical

The seepage rates at the centerline for the considered cases are given in Table 4-20 and Figure 4-34. It is seen that the variation of downstream slopes does not have considerable role on the performance of the chimney drain.

Table 4-20: Seepage rates at the centerline for varied downstream slopes of core with respect to *b/B*

	U/S 1V:0.5H ***D/S 1V :0.5H*** ***b/B*= 0.208**	***U/S 1V:0.5H*** ***D/S 1V :0.4H*** ***b/B*= 0.190**	***U/S 1V:0.5H*** ***D/S : 1V:0H*** ***b/B*= 0.131**
Seepage rate (l/h)	0.039	0.106	0.091

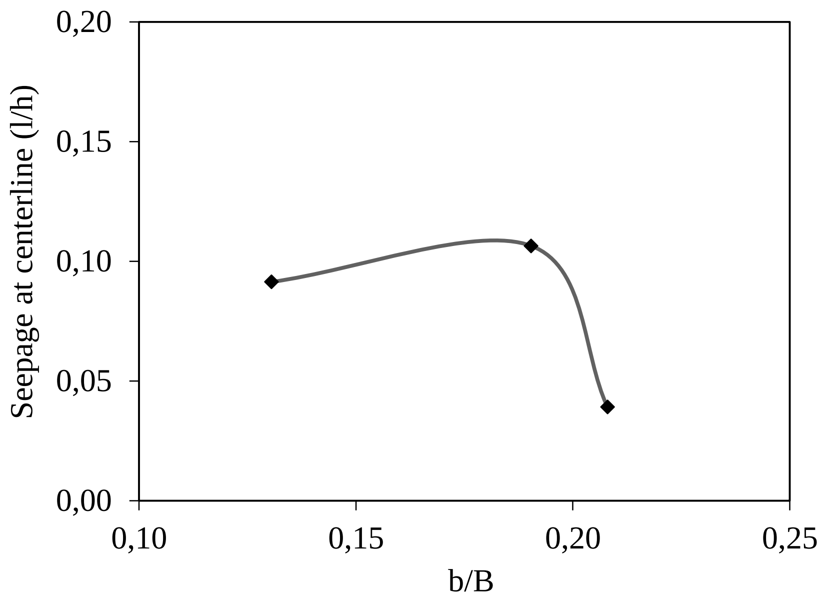

Figure 4-34: The graphical representation of the seepage flows at the centerline for varied downstream slopes of core with respect to *b/B*

4.5.3 The effects of the hydraulic conductivity

The hydraulic conductivity of the soil generally depends on its grain size distribution and its variation has significant effects on seepage through earth-fill dams (Çalamak and Yanmaz 2016). In order to assess the effect of the hydraulic conductivity variation on the drain effectiveness, it is halved and doubled by keeping the drain slope and the thickness constant. USBR (2011b) defines an empirical equation between the hydraulic conductivity and the grain size distribution for uniformly to moderately graded sand and gravel drains and filters. This equation is given below.

$$K = 0.35(D_{15})^2 \tag{4.5}$$

In above equation, K is the hydraulic conductivity of the drain and is in cm/s, and D_{15} is the particle size of the drain in mm for which 15% of the material is finer than that size. In the current study, the reference hydraulic conductivity of the chimney drain is selected as 1.0x10^{-4} m/s. In the analyses, this value is halved and doubled as 5.0×10^{-5} m/s and 2.0×10^{-4} m/s in two separate cases. According to the relationship given in Equation 4.5 D_{15} particle sizes are computed to be 0.12 mm and 0.24 mm for 2.0×10^{-4} m/s and 5.0×10^{-5} m/s, respectively. In the related design standards for drains and filters, the upper limit of D_{15} is given as 1.98 mm (USBR 2011a), whereas the lower limit is defined as 0.10 mm (USDA 1994). Therefore, these considered hydraulic conductivity values are found to be in the range of the appropriate particle sizes for the drains.

The change of the phreatic surface and the pore water pressures with respect to varied hydraulic conductivities of the drain are presented in Figure 4-35 and Table 4-21. According to the results, when the hydraulic conductivity increases the phreatic line becomes steeper in the core and the pore water pressures at the downstream part of the dam start to decrease. The percent difference of the pore water pressures are calculated according to the reference hydraulic conductivity and the results are given in Table 4-22.

Table 4-21: The pore water pressures at predefined points for various hydraulic conductivities of chimney drain

Point	K= 5x10^{-5} m/s	K= 1x10^{-4} m/s	K= 2x10^{-4} m/s
1	96.0	96.0	96.0
2	41.7	64.7	14.4
3	-120.1	-198.4	-195.9
4	235.7	235.7	235.7
5	150.3	179.5	115.0
6	-49.8	-53.2	-50.7

Note: The pore water pressure values are in kPa.

Table 4-22: The percent differences in pore water pressures for various hydraulic conductivity values of chimney drain

Point	K= 5x10^{-5} m/s	K= 1x10^{-4} m/s	K= 2x10^{-4} m/s
1	0.00	Reference Material	0.00
2	35.52		77.71
3	39.47		1.26
4	0.00		0.00
5	16.30		35.93
6	6.39		4.78

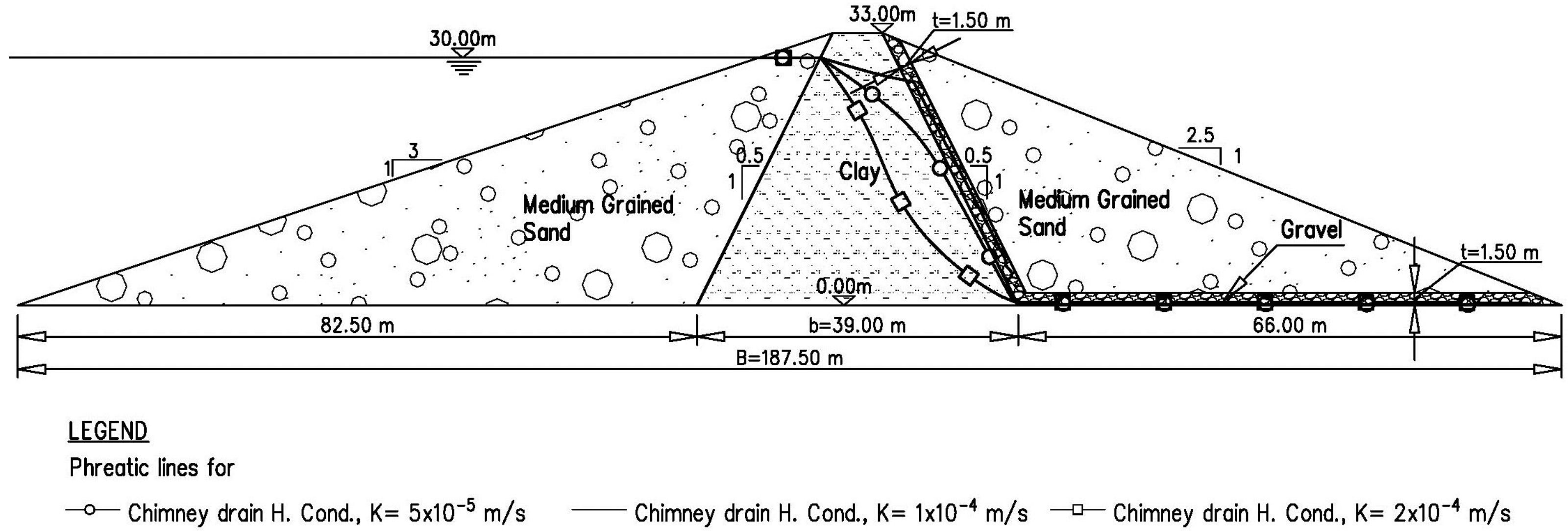

Figure 4-35: The phreatic surfaces for various hydraulic conductivities of the chimney drain

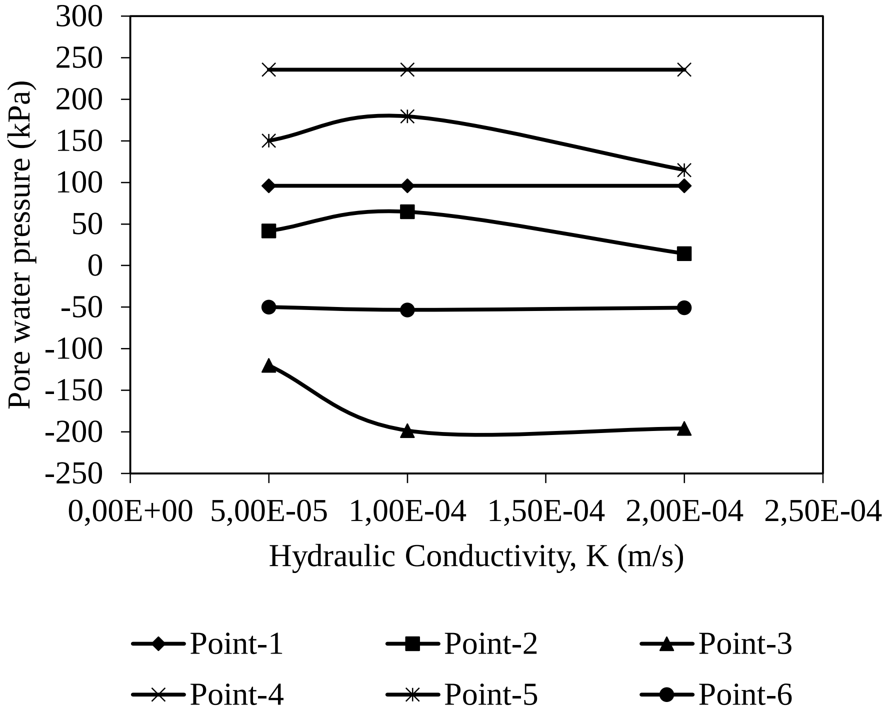

Figure 4-36: The pore water pressure values for various hydraulic conductivity values

The seepage rates at the centerline of the dam are given in Table 4-23 and Figure 4-37. According to the results, the core zone functions as an impervious barrier inside the dam. Therefore, the seepage rate is consistent for the varied hydraulic conductivity values.

Table 4-23: Seepage rates at the centerline for various hydraulic conductivity values of the chimney drain

	***K*= 5x10^{-5} m/s**	***K*= 1x10^{-4} m/s**	***K*= 2x10^{-4} m/s**
Seepage rate (l/h)	0.066	0.039	0.097

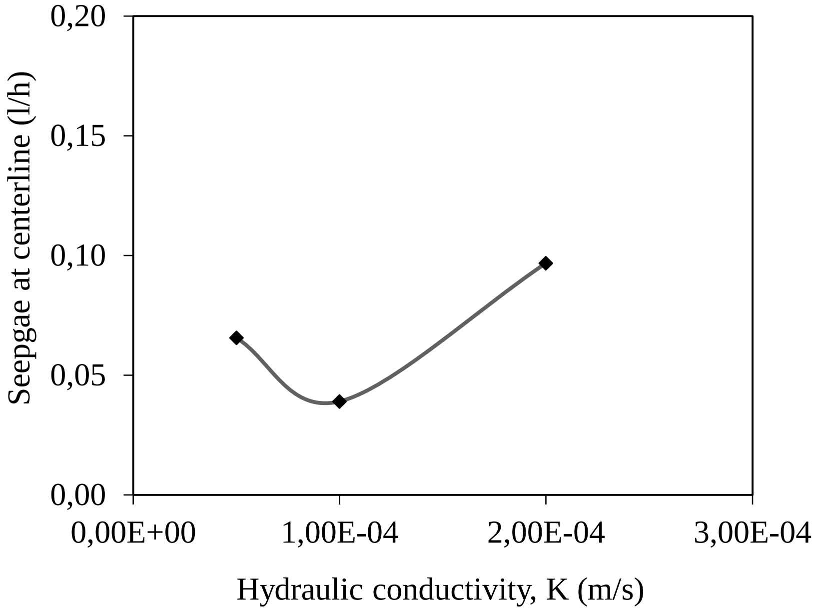

Figure 4-37: The graphical representation of the seepage flows at centerline for various hydraulic conductivity values of the chimney drain

4.6 Performance Assessment of Toe Drain

In this study, the effectiveness of both types of toe drain, which are described previously, are investigated. The layout of the considered toe drains are given in Figure 4-38 and Figure 4-39. At first, the toe drain without internal drainage facility is analyzed. In this part, the drain height and its hydraulic conductivity are changed to assess the performance of the drain. Analyzed cases for the toe drain are given in Figure 4-40.

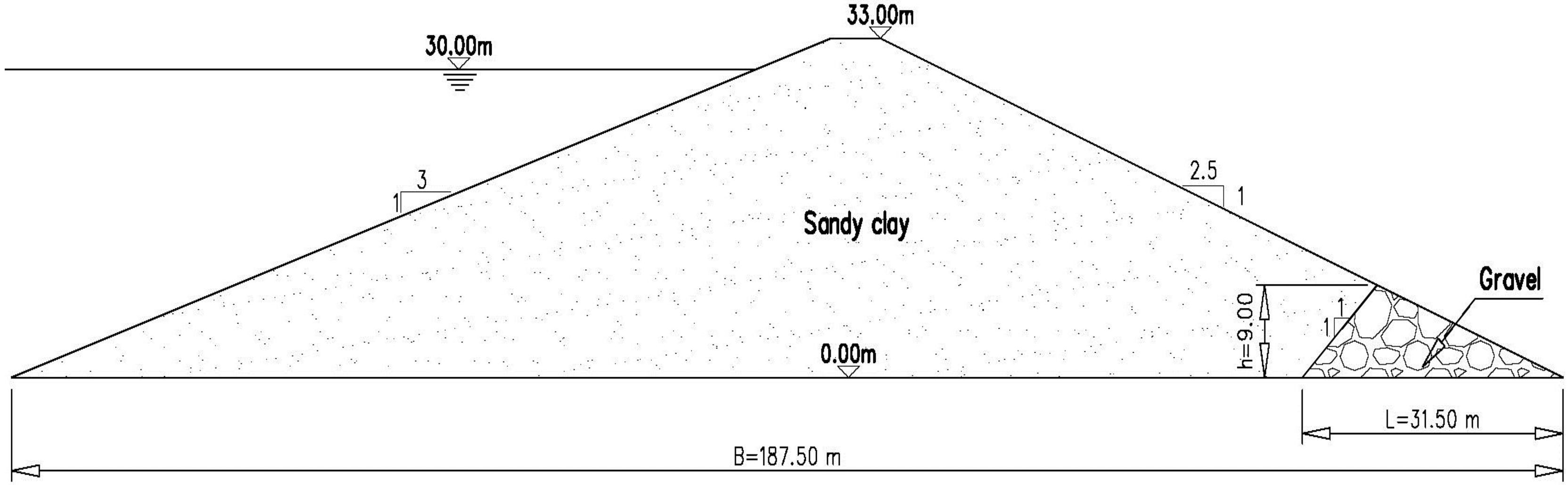

Figure 4-38: The toe drain without an internal drainage system

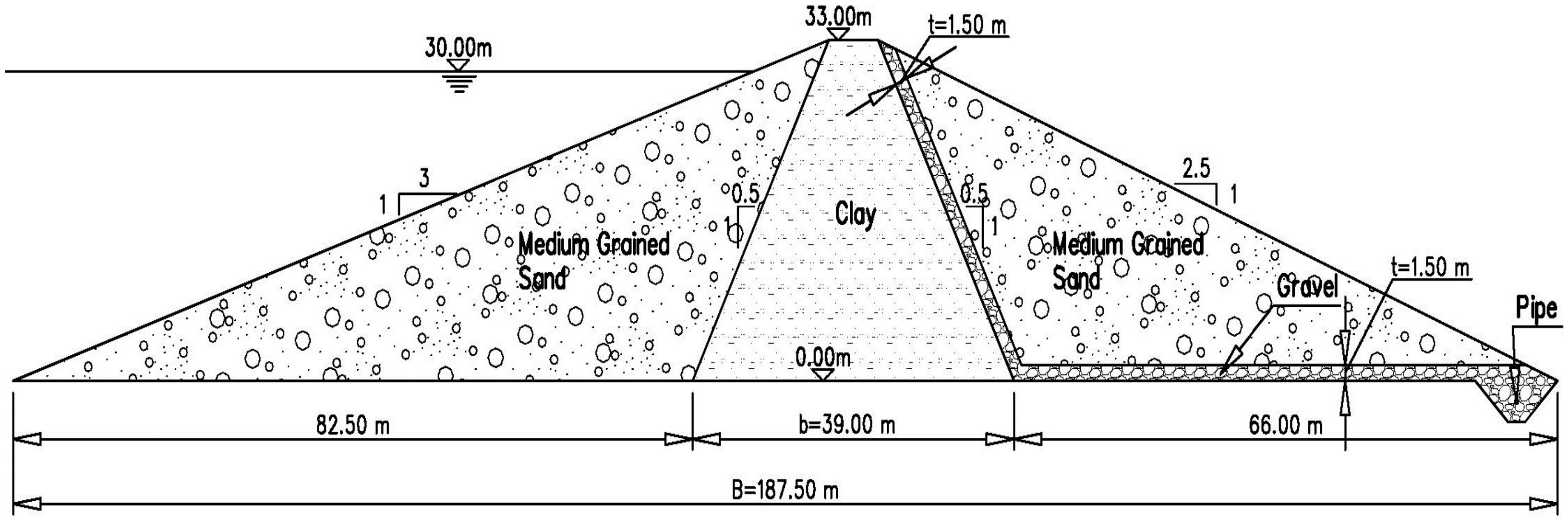

Figure 4-39: The toe drain with an internal drainage system

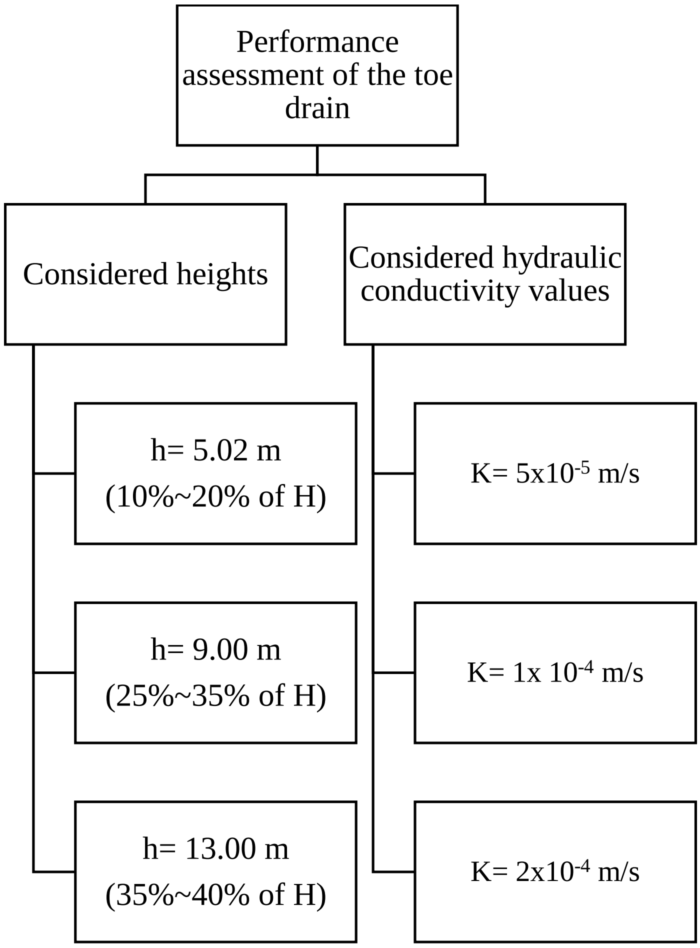

Figure 4-40: Investigated cases for the performance assessment of the toe drain

Then, the toe drains with internal drainage facility installed with blanket and chimney drains separately are analyzed for the same drain heights and hydraulic conductivity values of the toe drain. The effect of implemented toe drain is then investigated by comparing with the analyses conducted for drainage facilities without toe drain.

4.6.1 The Toe Drain without Internal Drainage

This type of toe drain is the most common drain type since its maintenance is relatively easier than that of the blanket and chimney drains (Sherard 1963). The conducted analyses for this drain type are explained below.

4.6.1.1 The effects of the drain height

The height of the drain is an important parameter in its design process and effectiveness in draining the seepage flow. In this study, the height of the toe drain is selected as 9 m regarding the criteria given in Creager et al. (1945) and Singh and Varshney (1995). In order to assess the effects of the toe drain height, the selected height is increased and decreased by 25%. The results of steady-state seepage flow analyses for the homogenous dam with 5.02 m, 9.00 m and 13.00 m high toe drains are presented in Figure 4-41 and Table 4-24. The graphical representation of pore water pressures at predefined points are given in Figure 4-42. The percent differences of pore water pressures according to reference height are given in Table 4-25. The seepage rates are obtained as well and shown in Table 4-26 and the graphical representation of the seepage values for varied toe drain heights are given in Figure 4-43. The results showed that higher toe drains result in slightly increased seepage flows through the dam. When the amount of granular material having a higher hydraulic conductivity than that of the homogeneous fill is increased, the seepage flow increases as well. Also, when the drain height is decreased, the elevations of the phreatic line in the downstream part increase. For the case with a 5.02 m high toe drain, the phreatic line meets with the downstream slope of the dam and this results in a seepage face at the downstream side. Therefore, it can be said that the performance of the toe drain is adversely affected by a decrease in its height. It is computed that toe drain whose height is 27% of the dam height is sufficient to effectively protect the downstream part from sloughing. Similar findings were also presented in Creager et al. (1945) and Singh and Varshney (1995).

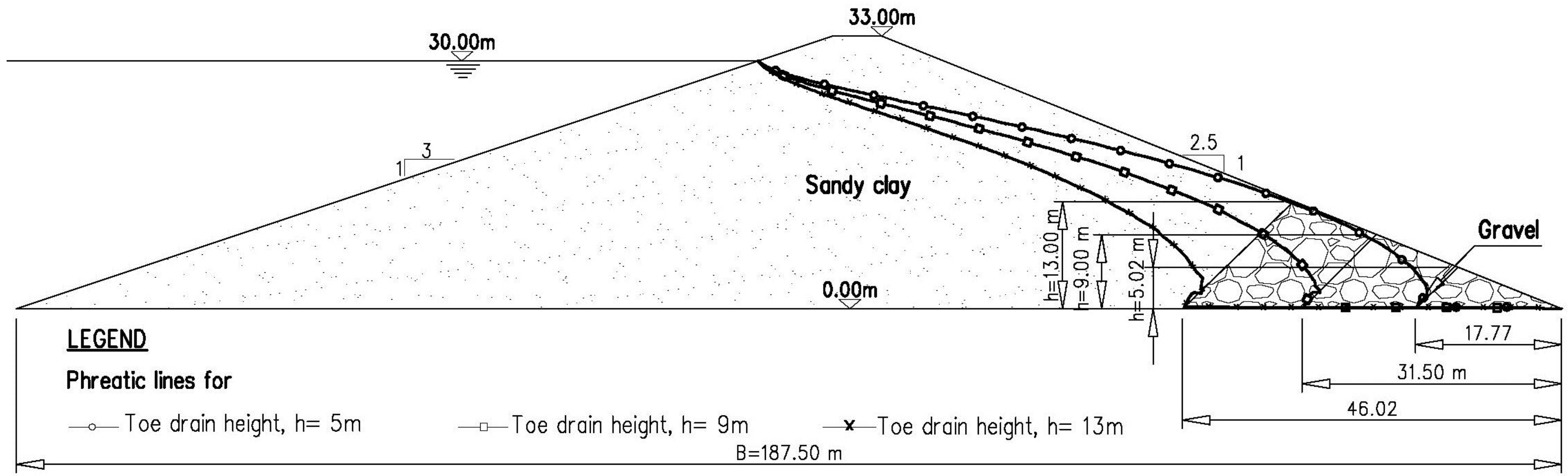

Figure 4-41: The phreatic lines for various heights of the toe drain without an internal drainage system

Table 4-24: The pore water pressures at predefined points for various heights of the toe drain without an internal drainage

Point	***h= 10~20% H*** ***h= 5.02 m***	***h= 25~35% H*** ***h= 9.00 m***	***h= 35~40% H*** ***h= 13.00 m***
1	92.7	92.1	91.2
2	55.8	46.0	35.7
3	-4.1	-24.8	-54.2
4	225.4	224.1	220.9
5	193.2	184.3	170.0
6	129.2	115.8	59.8

Note: The pore water pressure values are in kPa.

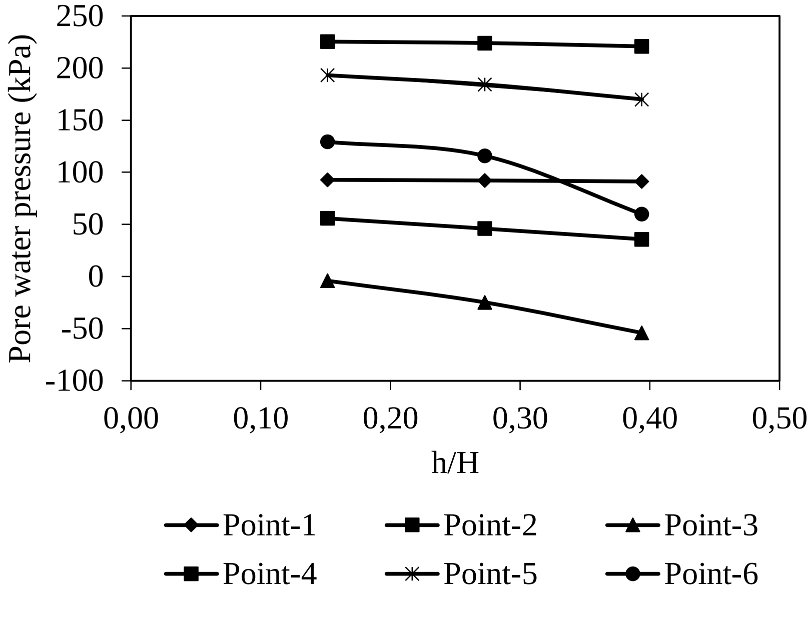

Figure 4-42: The graphical representation of the pore water pressure variation for the toe drain without an internal drainage

Table 4-25: The percent difference in pore water pressures for various heights of the toe drain

Point	*h*= 5.02 m *h/H*= 0.15	*h*= 9.00 m *h/H*= 0.27	h= 13.00 m *h/H*= 0.39
1	0.67		1.02
2	21.31		22.24
3	83.33	Reference	118.12
4	0.60	height	1.43
5	4.79		7.76
6	11.57		48.35

The seepage rates with respect to drain height is provided in Table 4-26 and Figure 4-43. According to the results, when the height of the toe drain is increased, the seepage passing through the dam centerline slightly increases.

Table 4-26: The seepage rates at the dam centerline with respect to toe drain height

	h= 5.02 m *h/H*= 0.15	*h*= 9.00 m *h/H*= 0.27	h= 13.00 m *h/H*= 0.39
Seepage rate (l/h)	0.18	0.21	0.25

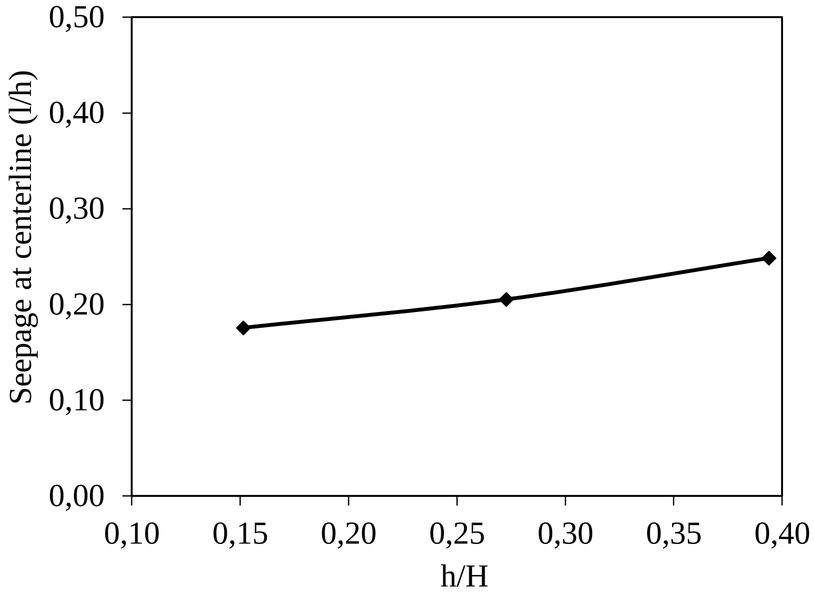

Figure 4-43: The graphical representation of the seepage rate at the dam centerline with respect to toe drain height

4.6.1.2 The effects of the hydraulic conductivity

The similar analyses conducted for the chimney drain are performed for the toe drain. The effects of the hydraulic conductivity of the drain on its effectiveness are investigated by varying it around its reference value. The toe drain selected for the homogenous dam is made of gravel and its hydraulic conductivity is determined as 1.0 x 10^{-4} m/s. This reference value is halved and doubled by keeping the drain height constant at 9 m. The halved and doubled hydraulic conductivity values correspond to D_{15} particle sizes of 0.12 mm and 0.24 mm, respectively, which are in the design limits (USBR 2011b and USDA 1994). The corresponding phreatic lines of the varied hydraulic conductivity of the toe drain are given in Figure 4-44. When the hydraulic conductivity is changed the phreatic surface of the seepage and the pore water pressures through the body do not change considerably. The reason is that the toe drain in all cases has provided sufficient hydraulic conductivity for the seepage. The pore water pressures for different hydraulic conductivity values of the toe drain at predefined points in the dam body are given in Table 4-27 and the graphical representation of these values are shown in Figure 4-45. The pore water pressures in predefined points do not change considerably. The percent differences at the pore water pressures with respect to the pressures observed for the case with the reference hydraulic conductivity are given in Table 4-28. The differences vary between 3% and 0% which means slight changes.

Table 4-27: The pore water pressures at predefined points for various hydraulic conductivity values of the toe drain without an internal drainage

Point	***K*= 5x10^{-5} m/s**	***K*= 1x10^{-4} m/s**	***K*= 2x10^{-4} m/s**
1	92.2	92.1	92.1
2	46.3	46.0	46.0
3	-24.0	-24.8	-24.8
4	224.1	224.1	224.1
5	184.7	184.3	184.3
6	106.3	106.3	106.3

Note: The pore water pressure values are in kPa.

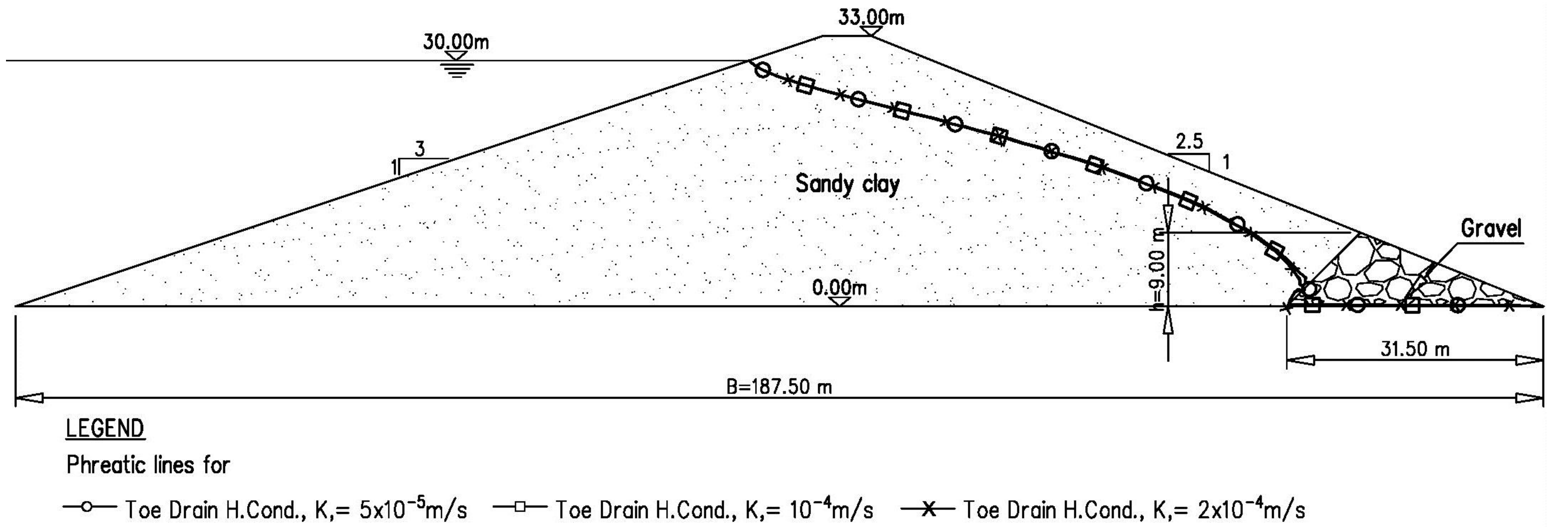

Figure 4-44: The phreatic lines for various hydraulic conductivities of the toe drain without an internal drainage system

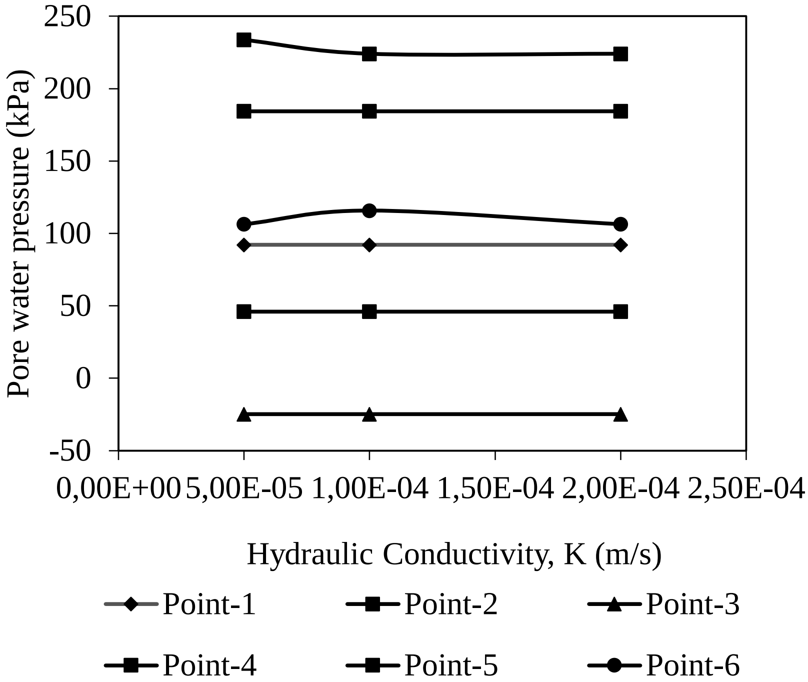

Figure 4-45: The graphical representation of the pore water pressure variation with respect to various hydraulic conductivities of the toe drain without an internal drainage

Table 4-28: The percent difference in pore water pressures for various hydraulic conductivities of toe drain

Point	***K*= 5x10^{-5} m/s**	***K*= 1x10^{-4} m/s**	***K*= 2x10^{-4} m/s**
1	0.03	Reference Material	0.00
2	0.67		0.01
3	3.30		0.08
4	0.04		0.00
5	0.19		0.00
6	0.01		0.02

In addition to pore water pressure values, the seepage rates of all cases having different hydraulic conductivities of the drain are represented in Table 4-29 and graphically shown in Figure 4-46. According to the results, seepage rates through the dam are not considerably affected by the variation of the hydraulic conductivity.

Table 4-29: The seepage rates at the dam centerline with respect to various hydraulic conductivities of the toe drain

	***K*= 5x10^{-5} m/s**	***K*= 1x10^{-4} m/s**	***K*= 2x10^{-4} m/s**
Seepage rate (l/h)	0.204	0.205	0.205

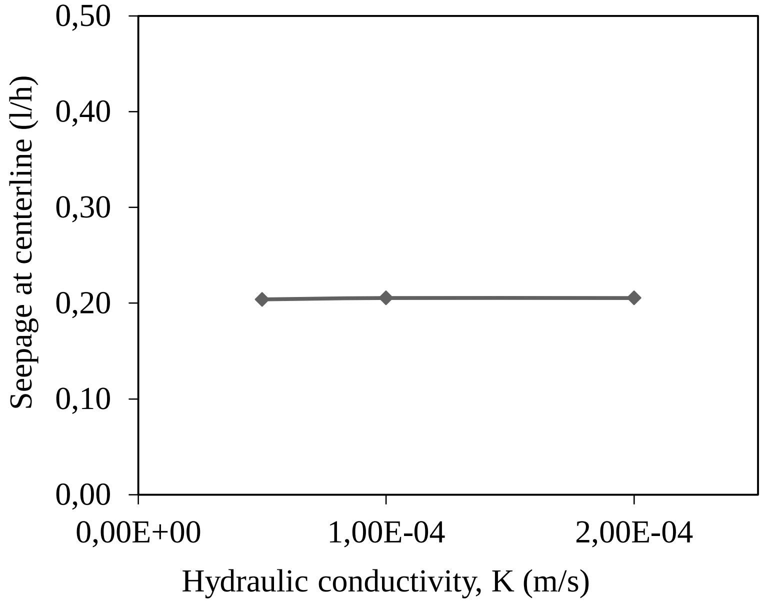

Figure 4-46: The graphical representation of the seepage rate at the dam centerline with respect to various hydraulic conductivities of the toe drain

4.6.2 Toe Drain with Internal Drainage

Toe drains may also be applied with an internal drainage system, such as blanket and chimney drains (Montana Department of Natural Resources 2010; USBR 1987). In these systems, generally a pipe is placed horizontally inside the drain and along the dam axis from one side of the dam to another. This pipe collects the water and discharges it to the tailwater channel. This kind of toe drain has limited geometrical properties. The recommended side slopes for the drain are 1V:1H, and the suggested height varies between 1 m and 4 m (Singh and Varshney 1995; USBR 1987). Considering these limitations, the dimensions of the toe drain applied in this study are determined. The detailed geometry of the drain is given in Figure 4-47.

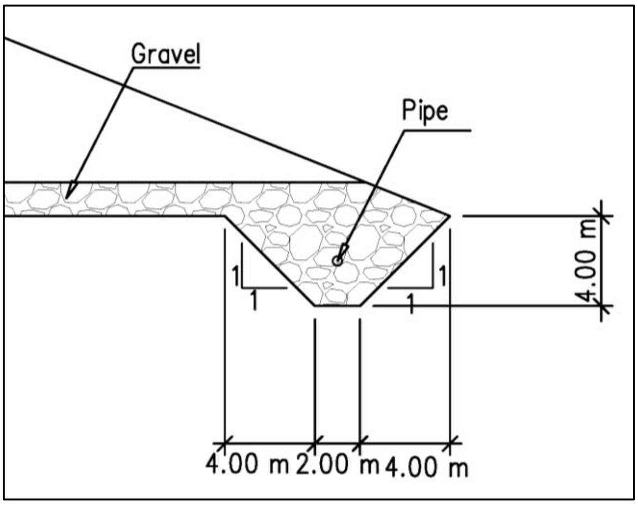

Figure 4-47: The detailed geometry of the toe drain with an internal drainage

The toe drain is applied along with blanket and chimney drains and seepage analyses are conducted. The phreatic lines of the cases having blanket with and without a toe drain are given in Figure 4-48. The pore water pressures at predefined points for these two cases are provided in Table 4-30. According to the results, when a toe drain is applied under the blanket drain, the phreatic line slightly moves towards upstream and the pore water pressures slightly decrease. It may be resulted that the toe drain increases the effectiveness of the blanket drain.

Table 4-30: The pore water pressures at predefined points for the blanket drain with and without a toe drain

Alternative	Point					
	1	***2***	**3**	***4***	***5***	***6***
Without the toe drain	92.0	46.4	-27.7	223.3	181.7	101.6

With the toe drain	92.2	48.3	-22.8	223.8	183.9	106.9

Note: The pore water pressure values are in kPa.

Similar analyses conducted for the blanket drain are held for the chimney drain. Chimney drain is applied on a simple zoned earth-fill dam with and without a toe drain. The analyses results are given in Figure 4-49 and Table 4-31. Similar findings are obtained for the chimney drain to those obtained for the blanket drain. When a toe drain is applied with the chimney drain the phreatic line elevation in the core particularly decreases and this results in decrease in pore water pressures in the core.

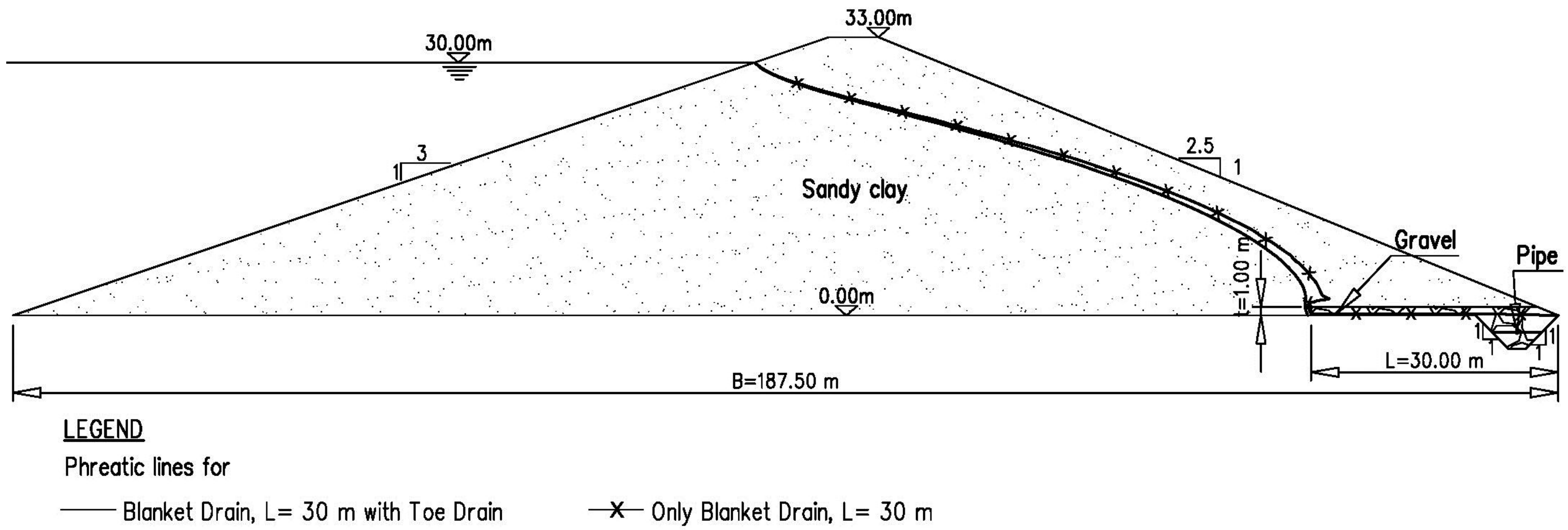

Figure 4-48: The phreatic surfaces for the blanket drain with and without a toe drain

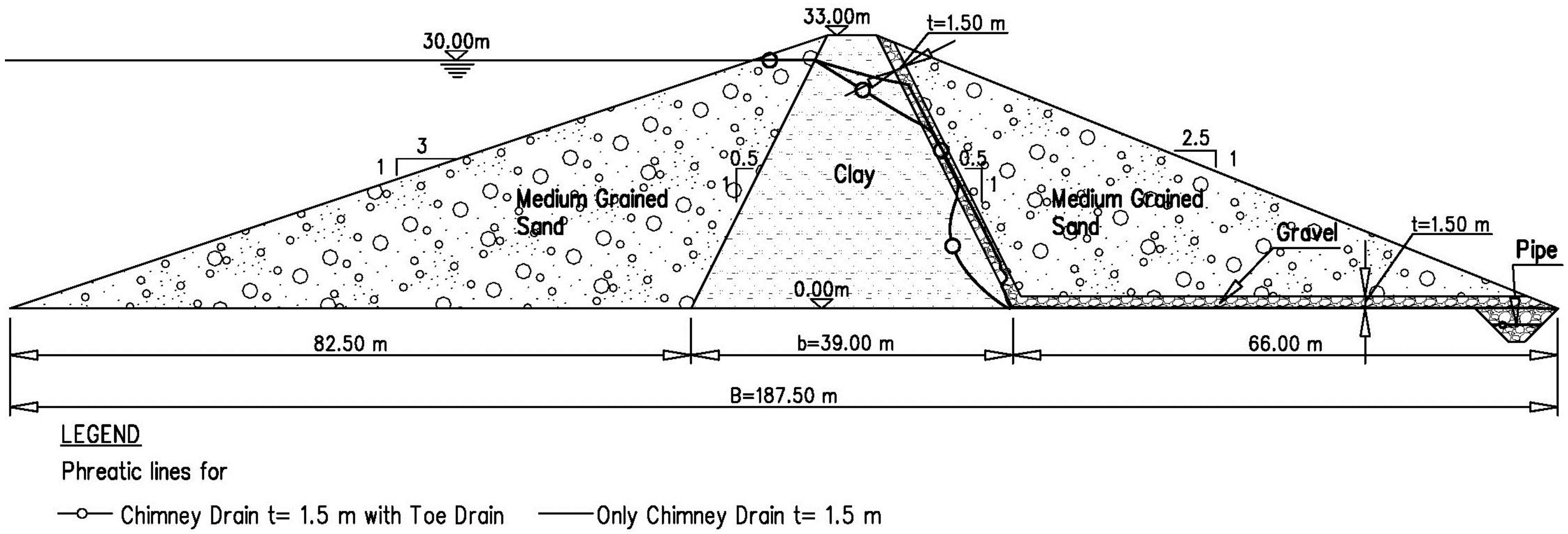

Figure 4-49: The phreatic surfaces for the chimney drain with and without a toe drain

Table 4-31: The pore water pressures at predefined points for the chimney drain with and without a toe drain

Alternative	Point					
	1	***2***	**3**	***4***	***5***	***6***
Without toe drain	96.0	64.7	-198.4	235.7	179.5	-53.2
With toe drain	96.0	44.4	-200.9	235.7	143.8	-55.7

Note: The pore water pressure values are in kPa.

According to the results given in Table 4-32, which shows the flow rates at the centerline, the implementation of a toe drain along with blanket and chimney drains increases their effectiveness. This allows the passage of higher discharges safely through the dam without creating a seepage face in the downstream side.

Table 4-32: The seepage rates at centerline for blanket and chimney drain with and without toe drain

	Drain Type			
	Blanket	**Blanket with Toe**	**Chimney**	**Chimney with Toe**
Seepage rate (l/h)	0.203	0.211	0.039	0.066

4.7 The Assessment of Anisotropy Effects on Performance of Drainage Facilities

The anisotropy of a soil is defined with the ratio of the vertical to horizontal hydraulic conductivity, which are K_V and K_H, respectively. As the dam materials are placed layer by layer, the soil becomes stiffer in vertical direction. Therefore, vertical hydraulic conductivity is generally less than that of the horizontal direction. In the current study, the dam materials are assumed to be homogenous and isotropic. However, the anisotropy effects are also investigated within the scope. The anisotropy ratios of the materials used in the application problems of the present study are determined from USBR (2011a). This ratio is determined for sandy clay as 0.143, for clay as 0.11, for medium grained sand as 0.2, and it is stated that the anisotropy can be neglected for coarse grained materials used in drains and filters. Therefore, it is recommended to take K_V/K_H as 1 for all drains types. The angle between the horizontal and the vertical directions of the hydraulic conductivity is assumed to be 90° for all materials.

The effects of the anisotropy are investigated for all drain types considered in the study, i.e., blanket, chimney and toe drains. The results are compared with those obtained for the isotropic cases of the related drain type. The blanket and toe drains are analyzed within the homogenous type earth-fill dam. The results for the homogeneous dam with the blanket drain are given in Figure 4-50 for isotropic and anisotropic material cases. For the anisotropic material case, the phreatic line is slightly shifted towards the downstream part of the dam. This is observed since the horizontal hydraulic conductivity is greater than the vertical one. This resulted small increases in pore water pressures at all points. The pore water pressures for isotropic and anisotropic cases are provided in Table 4-33. The seepage rate for the blanket drain for isotropic and anisotropic materials are given in Table 4-34. According to the results anisotropic material condition causes reduced fluxes. Chahar (2004) states for anisotropic dams that the length of the blanket drain needed to be increased in order to achieve the same efficiency with the dams having isotropic materials.

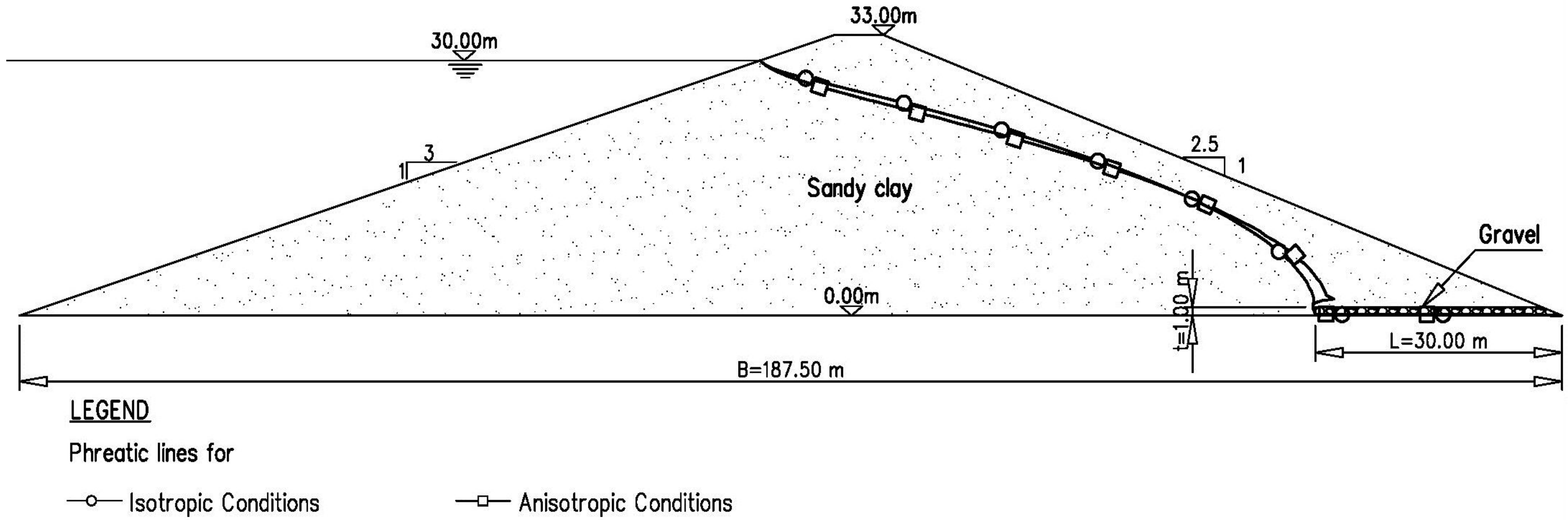

Figure 4-50: The phreatic lines of the homogenous dam with blanket drain for isotropic and anisotropic material cases

Table 4-33: The pore water pressures of the homogenous dam with blanket drain for isotropic and anisotropic material cases

Alternative	**Point**					
	1	***2***	**3**	***4***	***5***	***6***
Isotropic	92.2	48.3	-22.8	223.8	183.9	106.9
Anisotropic	95.7	57.7	-21.5	234.5	199.2	116.5

Note: The pore water pressure values are in kPa.

Table 4-34: The seepage rates at centerline for isotropic and anisotropic cases of the rate (l/h)

	Isotropic case	***Anisotropic case***
Seepage rate (l/h)	0.203	0.032

A similar analysis is conducted for the toe drain. The phreatic line comparisons for the isotropic and the anisotropic cases are presented in Figure 4-51. It is seen that the phreatic line negligibly moves towards the downstream. The pore water pressures for two different cases are shown in Table 4-35 and they do not considerably change through the body of the dam. In contrast to blanket drain, toe drain is not effected from anisotropic material condition of the shell, and shows sufficient performance since it covers the toe of the homogenous earth-fill dam.

The seepage rates of the dam with toe drain for isotropic and anisotropic materials are given in Table 4-36. The similar results obtained for the dam with blanket drain are observed for this case. According to the results, seepage through the dam decreased due to of the anisotropy of the material.

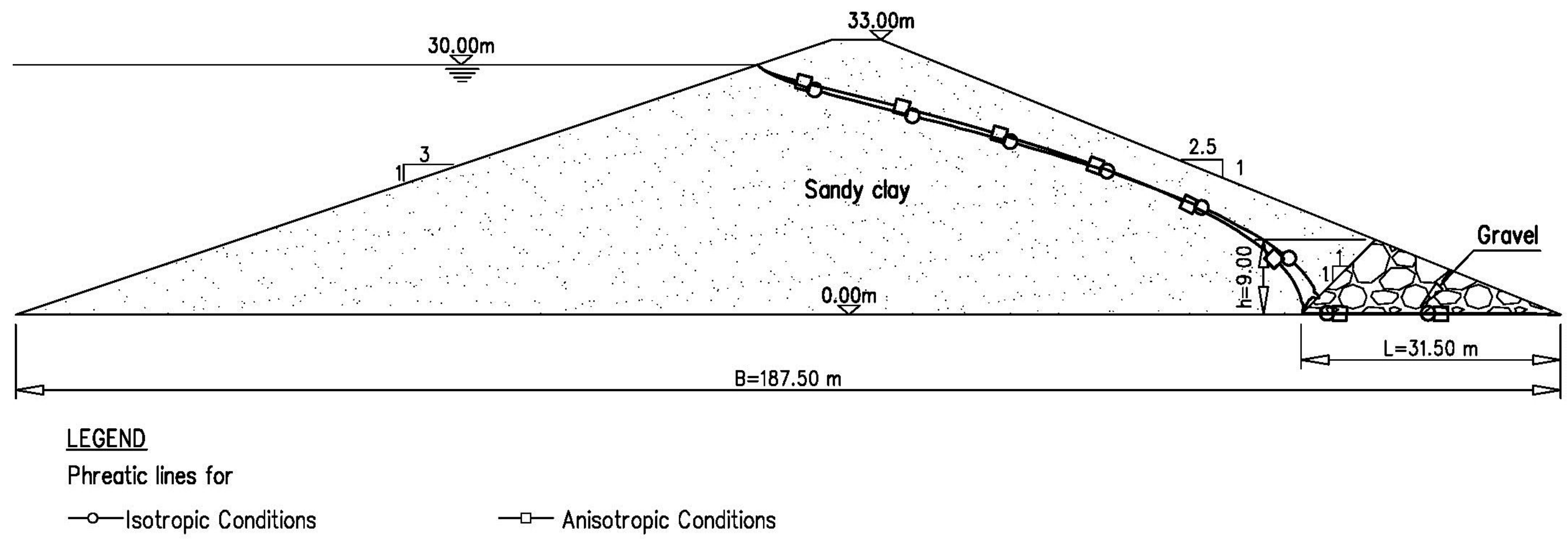

Figure 4-51: The phreatic lines of the homogenous dam with toe drain for isotropic and anisotropic material cases

Table 4-35: The pore water pressures of the homogenous dam with toe drain for isotropic and anisotropic material cases

Alternative	**Point**					
	1	***2***	**3**	***4***	***5***	***6***
Isotropic	92.1	46.0	-24.8	224.1	184.3	115.8
Anisotropic	95.7	44.8	-24.5	234.4	199.9	115.3

Note: The pore water pressure values are in kPa.

Table 4-36: The seepage rates at centerline for isotropic and anisotropic cases of toe drain

	Isotropic case	***Anisotropic case***
Seepage rate (l/h)	0.205	0.033

In anisotropic homogenous earth-fill dams, the phreatic line of the seepage commonly moves towards downstream direction since the dam body is composed of only one material. In anisotropic simple zoned earth-fill dams the core section has a greater anisotropy ratio than that of the shell zone due to the nature of the finer particles. This differentiates the phreatic line behavior in these types of dams. An anisotropic simple zoned earth-fill dam with chimney drain is analyzed for the seepage through its body and the results are compared with those obtained for the case having isotropic materials. The phreatic line positions for isotropic and anisotropic material cases are given in Figure 4-52. Since the clay has relatively greater anisotropy ratio, abrupt changes are observed in the phreatic surface in that region. This also resulted in considerable changes in the pore water pressures, particularly at Points 2 and 5, which rest inside the core (see Table 4-37). However, these abrupt changes do not affect the performance of the chimney drain. The seepage rates of the dam having chimney drain for isotropic and anisotropic material cases are given in Table 4-38. It is seen that the seepage rate reduces in simple zoned earth-fill dams having chimney drains for the anisotropic material condition.

Table 4-37: The pore water pressures of the simple zoned dam with chimney drain for isotropic and anisotropic material cases

Alternative	**Point**					
	1	***2***	**3**	***4***	***5***	***6***
Isotropic	96.0	64.7	-198.4	235.7	179.5	-53.2
Anisotropic	96.0	56.9	-197.9	235.7	196.2	-52.7

Note: The pore water pressure values are in kPa.

Table 4-38: The seepage rates at centerline for isotropic and anisotropic cases of chimney drain

	Isotropic case	***Anisotropic case***
Seepage rate (l/h)	0.039	0.006

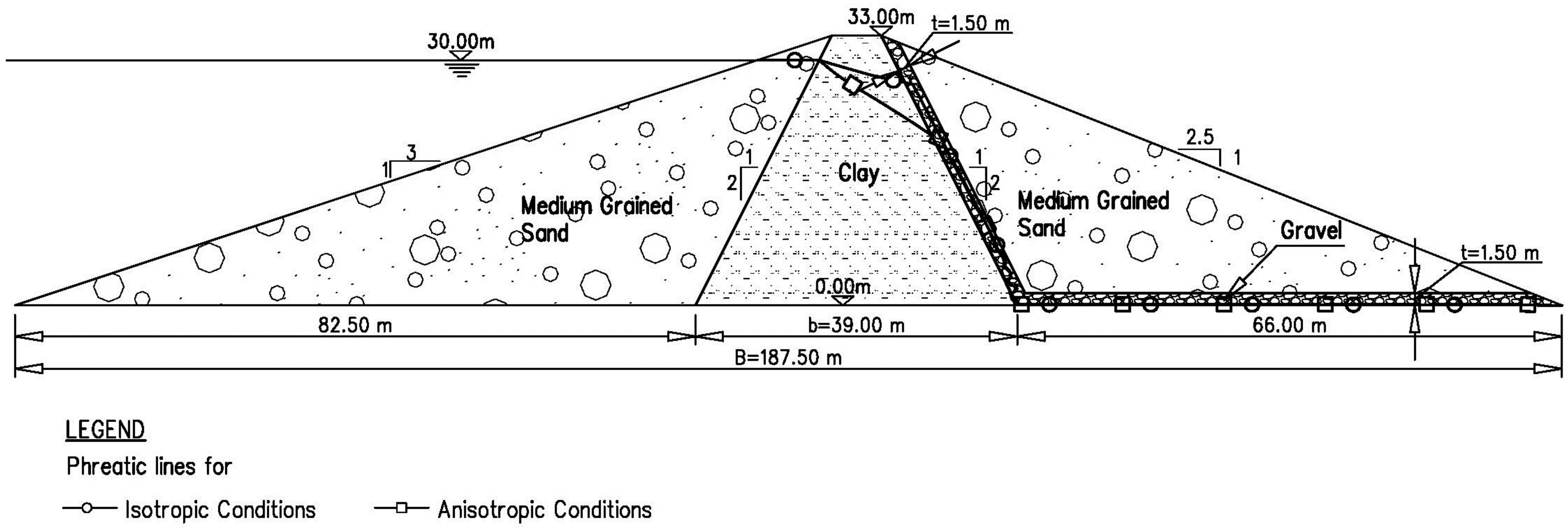

Figure 4-52: The phreatic lines of the simple zoned dam with chimney drain for isotropic and anisotropic material cases

4.8 The Effectiveness of Drainage Facilities on Reduction of the Internal Stresses

The type of the drain may affect the total stress distribution through an earth-fill dam. In the scope of the study, these effects are also investigated by using a finite element software SIGMA/W (Geo-Slope Int Ltd. 2014b). The stress distributions of the homogeneous dam with blanket and toe drains and the simple zoned dam with chimney drain are assessed. The hydraulic conductivity and the water contents of the soils are kept at their reference values. The unit weight, modulus of elasticity and Poisson's ratio values of clay, sandy clay, medium grained sand and gravel are determined from USBR (1987) and Bowles (1996), and they are supplied in Table 4-39. In order to determine the total stresses, the pore water pressures, which are previously computed, are used. The total stresses are obtained at six different points which are shown in Figure 4-2. The total stresses in predefined points without drainage facilities are also computed. The total stresses are compared with and without drain in both homogenous and simple zoned type earth-fill dams. The results of the stress analyses are provided in Table 4-40 and Table 4-41.

Table 4-39: Material properties for stress analyses

Materials	***Unit Weight, γ*** **(kN/m³)**	***Modulus of Elasticity, E*** **(kPa)**	***Poisson's Ratio, μ***
Clay	16.7	25000	0.45
Sandy Clay	18.2	40000	0.30
Medium Grained Sand	19.8	60000	0.20
Gravel	19.5	150000	0.10

The results showed that in the homogenous type earth-fill dam with drainage facilities, the total stresses at Points 1, 2 and 3 are reduced. The most affected points are determined to be Point 3 and Point 6.

Table 4-40: Total stresses developed in the homogeneous dam with and without drain facilities

Drain Type	**Directions**	**Point**					
		1	**2**	**3**	**4**	**5**	**6**
Dam without drain	X	116.3	97.3	27.0	295.5	284.1	212.2
	Y	133.4	211.4	42.1	387.5	446.4	311.9
	Z	113.4	118.8	20.4	294.9	299.5	214.3
Blanket	X	116.0	91.5	24.8	294.6	281.5	200.8
	Y	133.1	209.6	43.6	385.7	447.1	293.5
	Z	113.3	113.8	20.5	293.5	296.7	203.5
Blanket with toe	X	115.9	90.9	24.6	294.9	280.8	198.6
	Y	133.1	210.4	43.7	383.7	447.2	315.3
	Z	113.2	113.5	20.5	293.5	295.9	201.5
Toe	X	115.8	84.4	23.4	294.5	281.4	200.9
	Y	133.1	202.8	43.6	383.9	446.3	317.8
	Z	113.2	107.2	20.1	293.3	296.4	204.2

Note: The total stress values are in kPa.

In the simple zoned earth-fill dam, without chimney drain, presence of core material leads downstream part to stay unsaturated. When chimney drain is implemented, all the seepage discharges within the drain; therefore, downstream part of the dam stays unsaturated. In the simple zoned earth-fill dam, the total stresses do not vary considerably when chimney drain is implemented.

Table 4-41: Total stress values developed in the simple zoned type earth-fill dam with and without chimney drain

Drain Type	Directions	Point					
		1	2	3	4	5	6
Dam without drain	X	123.0	87.2	57.0	294.0	358.1	85.8
	Y	132.0	242.1	47.4	393.0	450.2	300.4
	Z	108.6	154.5	20.9	277.6	380.7	77.2
Chimney	X	121.7	96.9	57.5	292.6	357.0	82.9
	Y	132.4	238.7	42.7	394.0	441.7	306.3
	Z	108.4	158.7	20.9	278.0	377.1	77.9
Chimney with toe	X	122.3	89.3	58.1	293.5	363.3	86.2
	Y	132.1	242.5	47.8	393.0	452.5	308.9
	Z	108.5	156.0	21.2	277.5	384.7	79.0

Note: The total stress values are in kPa.

CHAPTER 5

DISCUSSION OF RESULTS

The results of the analyses conducted for blanket drain cases showed that when the length of the blanket drain was increased, the elevation of the phreatic line decreased at the downstream part of the dam. This also results in decreases in pore water pressures. The seepage rate increases when the length of the blanket drain is increased. This resulted from the increased hydraulic gradients through the body. It is seen that, when the length of the blanket drain is extended towards the upstream part, the seepage rate increases. In the current study, an exponential relation is found between seepage rate and the blanket drain length to dam base width ratio. When thickness of the blanket is increased, it is seen that the seepage rate and the phreatic line are slightly affected. According to the results, when the thickness is doubled, the seepage flow is decreased only by 5%. Therefore, it may be said that, the length of the blanket drain is an important parameter for its effectiveness. The blanket drain length is needed to be determined considering the design limitations because excessive pore water pressures through the dam may occur and this might cause stability problems.

In the scope of the study, the performance of the chimney drain is also investigated. The results showed that there was no considerable effects of drain slopes on the seepage passing through the dam. Therefore, the volume of the core zone can be minimized in design process without affecting the performance of the drain. The analyses also showed that when the thickness of the chimney drain was less than 1.5 m, it was not able to discharge seepage flow sufficiently.

In such cases, the phreatic surface moves towards to downstream part of the shell and seepage faces may occur. The effects of material properties of the chimney drain on the phreatic surface and the pore water pressures are also investigated. Alternative cases are analyzed for different D_{15} particle sizes which determine the hydraulic conductivity of the drain. Increased sizes of D_{15} causes decreased pore water pressures at the downstream part of the dam.

Analyses for assessment of toe drain performance are conducted for various height and material properties of the drain. It is resulted that higher the drain height, slightly higher the seepage rates. When the height of the toe drain is decreased the phreatic line may intersect the downstream side and this might cause a seepage face. It is shown that the toe drain height may be taken as 27% of the total dam height to protect the downstream slope of the earth-fill dam. It is also seen that, D_{15} particle size does not considerably affect the toe drain performance due to sufficient conductivity of the drain for the cases in which hydraulic conductivity is halved and doubled.

Also the effects of the material anisotropy are investigated for all type of drains considered in this study. When the material anisotropy is considered, the phreatic line moves towards the downstream part of the homogenous earth-fill dam. The blanket drain in homogenous earth-fill dam is not able to sufficiently reduce the phreatic line elevations in the downstream part in anisotropic material condition. Therefore, the blanket drain length needed to be increased to achieve the same efficiency with that of the isotropic material condition. The performance of the toe drain is seen to be not affected from anisotropic material condition of the dam. It is seen to have sufficient efficiency to discharge the seepage even in anisotropic material conditions. In the simple zoned type earth-fill dam the presence of impervious core prevent the phreatic line from moving towards the downstream slope. Therefore, the chimney drain performance is almost not affected from anisotropic material conditions of the dam.

In the scope of the study, stress analyses are also conducted to assess the ability of the drains in decreasing the total stresses. Dams with and without drainage facilities are studied and results showed that when the drainage system is implemented to the homogenous dam, the total stress decreases and the elevation of the phreatic line at downstream part reduces as well. It is seen that the stress distribution through the simple zoned type earth-fill dam is not affected much with the installation of a chimney drain.

CHAPTER 6

CONCLUSIONS

6.1 Summary

The determination of type, dimensions and material properties of drainage facilities is one of the major parts of the earth-fill dam design procedure. The current study is focused on assessment of performance and effectiveness of common drainage structures used in earth-fill dams i.e. blanket, chimney and toe drains. The performance of a drain is considered to be a function of its geometric and material properties. To this end, length and thickness of the blanket drain, thickness and material properties of chimney drain, and slopes, height and material properties of the toe drain are varied. Additionally, effects of the material anisotropy on the performance of drainage structures and the ability of drains in reducing the total stresses developing through the dam body are studied. The steady-state seepage analyses are conducted with SEEP/W software, whereas the stress distributions are assessed with SIGMA/W.

6.2 Major Findings of the Study

The main findings of the study are summarized below.

- The height of dam does not affect its seepage behavior and the performance of the drains.
- When the length of the blanket drain is increased the seepage rate increases. An exponential relation is found between the seepage rate and

the drain length to dam base width ratio. If the drain length is relatively short, a seepage face may develop in the downstream side of the dam. When the length of the blanket drain is relatively long, it causes abrupt pore water pressure changes. The performance of the blanket drain is not considerably affected by its thickness. The pore water pressures developing at the downstream part are only affected by the thickness. However, the changes in pressure are slight. Besides, the seepage rate at the dam centerline decreases only by 5% even the reference thickness is doubled. It may be concluded that, thickness of the blanket drain does not have significant role on drainage performance.

- The conducted analyses of chimney drain shows that the pore water pressures and the seepage flow are not affected considerably when the drain slopes are changed. Therefore, it can be said that, when the cross-sectional area of the core of dam is maximized, chimney drainage might not be needed. Instead, a blanket drain may be used. The variation of the thickness affects the drain performance. If the thickness of chimney drain is altered, the pore water pressures change slightly. Selecting thicker drains are more reasonable for keeping the phreatic line within the drain and protecting downstream part from sloughing. Higher hydraulic conductivity of the drain results in steeper phreatic line within the core zone. Therefore, it is seen that when D_{15} of the chimney drain material is increased, the pore water pressures decrease in the downstream part of the earth-fill dam.
- When the height of the toe drain is increased, the seepage rate increases slightly, and the phreatic line elevations decrease in the downstream part. It is observed that a drain with a height which is at least 27% of the dam height has an effective performance in protecting the downstream part from sloughing. When the hydraulic conductivity of the drain is halved and doubled, the phreatic line is affected slightly due to sufficient discharge capacity of the drain. Therefore, the seepage rate almost stays constant for varying hydraulic conductivities of the drain.

- The application of toe drain with internal drainage systems increases the effectiveness of the drainage facility. The ability of transmitting the seepage flow increases both in homogenous and simple zoned type earth-fill dams with toe drains. The elevations of phreatic line in the downstream part of the dam decreases for homogenous type earth-fill dam. Therefore, pore water pressures slightly decrease. Similar results are obtained in the simple zoned type earth-fill dams.
- When the horizontal hydraulic conductivity is higher than the vertical one, the phreatic line moves towards the downstream slope and seepage face may occur especially in homogenous type earth-fill dam with blanket or toe drains. However, the presence of the core prevents the downstream slope from sloughing in simple zoned type earth-fill dam. The anisotropy affects seepage rate through the dam as well. The flux decreases when anisotropy of the soil is considered.
- The results of the stress analyses shows that drains also affect the stress distribution through the dam body. The drainage facilities protect downstream slope from sloughing and reduce the stresses within the dam especially at the downstream part. The results for the simple zoned type earth-fill dam showed that stress distributions inside the dam are not considerably affected due to presence of impervious core, which protects the downstream part from negative effects of seepage

6.3 Suggested Future Research

This study investigated the effectiveness of drain types commonly used in earth-fill dams under steady-state flow conditions. In a prospective study which will base on this research should consider transient flow with various boundary conditions, such as rapid fill and drawdown. Furthermore, the foundations of the dams considered can be modeled as pervious zones and the performance of a relief well installed to drain the seepage flow at the foundation can be investigated.

REFERENCES

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

Bilgi, V. (1990). *Toprak ve Kaya Dolgu Barajların Projelendirme Kriterleri*. The General Directorate of State Hydraulic Works of Turkey (DSI).

Bowles, J. E. (1996). *Foundation Analysis and Design*. New York: McGraw-Hill.

Bureau of Indian Standards. (1988). "I.S. Code (12169-1987). Criteria for Design of Small Embankment Dams."

Carsel, R. F., and Parrish, R. S. (1988). "Developing Joint Probability Distributions of Soil Water Retention Characteristics." *Water Resources Research*, 24(5), 755–769.

Carter, M., and Bentley, S. P. (1991). *Correlations of Soil Properties*. *Correlations of soil properties*, Pentech Press, distributed by Wiley.

Cedergren, H. R. (1967). *Seepage, Drainage, and Flow Nets*. New York: Wiley.

Chahar, B. R. (2004). "Determination of Length of a Horizontal Drain in Homogeneous Earth Dams." *Journal of Irrigation & Drainage Engineering*, 130(6), 530–536.

Creager, W. P., Justin, J. D. W., and Hinds, J. (1945). *Engineering for Dams*. New York, J. Wiley & Sons, inc.; London, Chapman & Hall, ltd.

Çalamak, M., and Yanmaz, A. M. (2016). "Uncertainty Qualification of Transient Unsaturated Seepage through Embankment Dams." *International Journal of Geomechanics*, in press.

Çalamak, M., Yanmaz, A. M., and Kentel, E. (2014). "Uncertainty Based Analysis of Seepage through Earth-Fill Dams." PhD Thesis, Middle East Technical University.

Das, B. M. (2016). *Principles of Foundation Engineering*. Stanford, CT : Cengage Learning.

Djehiche, A., Amieur, R., and Gafsi, M. (2012). "Seepage through Earth Dams with Chimney Drain on Pervious Foundation." *Advanced Materials Research*, 452(1), 538.

Djehiche, A., Amieur, R., and Gafsi, M. (2014). "The Seepage through the Earth Dams with a Vertical Drain : an Experimental Study." *Journal of Environmental Research And Development*, 8(3), 471–476.

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

Foster, M., Fell, R., and Spannagle, M. (2000). "The Statistics of Embankment Dam Failures and Accidents." *Canadian Geotechnical Journal*, 37(1992), 1000–1024.

Fredlund, D. G., and Xing, A. (1994). "Equations for the Soil-Water Characteristic Curve." *Canadian Geotechnical Journal*, NRC Research Press, 31(4), 521–532.

Geo-Slope Int Ltd. (2015). *Seepage Modeling with SEEP/W*. Geo-Slope International Ltd., Calgary.

Geo-Slope Int Ltd. (2014a). "Groundwater Seepage Analysis with SEEP/W." Calgary, Alberta, Canada.

Geo-Slope Int Ltd. (2014b). *Stress-Deformation Modelling with SIGMA/W*.

Golze, A. R. (1977). *Handbook of Dam Engineering*. New York : Van Nostrand Reinhold Co.

Green, R. E., and Corey, J. C. (1971). "Calculation of Hydraulic Conductivity: A Further Evaluation of Some Predictive Methods." *Soil Science Society of*

America Journal, Soil Science Society of America, Madison, WI, 35, 3–8.

Jansen, R. B. (1988). *Advanced Dam Engineering for Design, Construction, and Rehabilitation*. New York : Van Nostrand Reinhold.

Justin, J. D. W. (1932). *Earth Dam Projects*. New York : J. Wiley & Sons, Inc.

Kovács, G. (1981). "Seepage Hydraulics." *Developments in Water Science Volume 10*, G. Kovács, ed., Elsevier Science, Amsterdam.

Malekpour, A., Farsadizadeh, D., Hosseinzadeh Dalir, A., and Sadrekarimi, J. (2012). "Effect of Hrizontal Drain Size on the Stability of an Embankment Dam in Steady and Transient Seepage Conditions." *Turkish Journal of Engineering and Environmental Sciences*, 36(2), 139–152.

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." *Journal of Civil Engineering and Urbanism*, Science Line Publication, 3(3), 114–121.

Maslia, M. L., and Aral, M. M. (1982). "Evaluation of a Chimney Drain Design in an Earthfill Dam." *Ground Water*, 20(1), 22–31.

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.

Mishra, G. C., and Singh, A. K. (2005). "Seepage through a Levee." *International Journal of Geomechanics*, 5(1), 74–79.

Montana Department of Natural Resources, D. S. P. (2010). "Technical Note 4 Chimney Filter / Drain Design and Construction Considerations."

Mualem, Y. (1976). "A New Model for Predicting the Hydraulic Conductivity of Unsaturated Porous Media." *Water Resources Research*, 12(3), 513–522.

P.S. Abhilasha, M., and Balan, T. G. A. (2014). "Numerical Analysis of Seepage in Embankmnet Dams." *IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)*, e-ISSN: 22, 13–23.

Rawls, W. J., Brakensiek, C. L., and Saxton, K. E. (1982). "Estimation of Soil

Water Properties.” *Transactions - American Society of Agricultural Engineers*, 25(5), 1316–1320,1328.

Richards, L. A. (1931). “Capillary Conduction of Liquids Through Porous Mediums.” *Physics (0148-6349)*, 1(5), 318.

Sharma, R. P., and Kumar, A. (2013). “Case Histories of Earthen Dam Failures.” *International Conference on Case Histories in Geotechnical Engineering. 8*, Missouri University of Science and Technology, Chicago, Illinois, 29.4.2013-04.05.2013.

Sherard, J. L. (1963). *Earth and Earth-Rock Dams; Engineering Problems of Design and Construction.* New York, Wiley.

Singh, B., and Varshney, R. S. (1995). *Engineering for Embankment Dams*. Brookfield, VT : A.A. Balkema Publishers.

Taft, B. Speck, S. W., and Morris, J. R. (1994). “Dam Safety: Earth Dam Failures.” *Ohio Department of Natural Resources Division of Water*, 94–30.

Tayfur, G., Swiatek, D., Wita, A., and Singh, V. P. (2005). “Case Study: Finite Element Method and Artificial Neural Network Models for Flow through Jeziorsko Earthfill Dam in Poland.” *Journal of Hydraulic Engineering*, American Society of Civil Engineers, 131(6), 431–440.

Taylor, D. W. (1948). *Fundamentals of Soil Mechanics*. New York, J. Wiley, 1948.

Terzaghi, K., Peck, R. B., and Mesri, G. (1996). *Soil Mechanics in Engineering Practice*. Wiley-Interscience publication, Wiley.

USACE. (1994). “Seepage Analysis and Control for Dams, EM-1110-2-1901.” *U.S. Army Corps of Engineers*.

USBR. (1987). *Design of Small Dams*. U.S. Dept. of the Interior, Bureau of Reclamation.

USBR. (2011a). *Design Standards No. 13 Embankment Dams Chapter 8:*

Seepage Phase 4 (Final). U.S. Dept. of the Interior, Bureau of Reclamation.

USBR. (2011b). *Design Standards No. 13 Embankment Dams Chapter 5: Protective Filters Phase 4 (Final)*. U.S. Dept. of the Interior, Bureau of Reclamation.

USBR. (2012). *Design Standards No. 13 Embankment Dams Chapter 2: Embankment Design Phase 4 (Final)*. U.S. Dept. of the Interior, Bureau of Reclamation.

USDA. (1994). “Gradation Design of Sand and Gravel Filters.” *National Engineering Handbook*, United States Department of Agriculture (USDA), Washington, D.C.

van Genuchten, M. T. (1980). “A Closed-Form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils.” *Soil science society of America journal*, Soil Science Society of America, 44(5), 892–898.

Wang, H., and Anderson, M. P. (1982). *Introduction to Groundwater Modelling : Finite Difference and Finite Element Method*. (L. Olsen, ed.), W. H. Freeman and Company, San Francisco.

West, T. R. (1995). *Geology Applied to Engineering*. Prentice Hall.