EFFECTS OF BERM CHARACTERISTICS ON EARTH-FILL DAM STABILITY

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ABSTRACT

EFFECTS OF BERM CHARACTERISTICS ON EARTH-FILL DAM STABILITY

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One of the causes of failure in earth-fill dams is the slide of the slope. For this reason, slope stability is a crucial issue for dam safety. There are some precautions to increase the safety of earth-fill dams, and constructing berms on upstream or downstream sides is one of these ways. In this study, effects of berm properties on dam stability are investigated with a case study. The effects of different berm heights, numbers and widths on the stability of Hancağız Dam, Turkey, are analyzed by using three software. The safety factors of slopes, seepage rates through the body, and the pore water pressures in the embankment are obtained under steady-state, rapid fill, and rapid drawdown conditions. Results show that increasing the berm height, number or width of berms provides higher safety factors for the slope where berm is built on. Increasing the berm height is beneficial up to a certain level. Further increase in the berm height causes lower safety factors for the slope. Any changes made on upstream berms do not affect the safety of the downstream slope and vice versa. It is also found that the berm geometry has negligible effect on water flux and pore water pressure in the embankment.

Keywords: Earth-fill dam, berm, seepage analysis, slope stability analysis, finite element method

ÖZ

PALYE ÖZELLİKLERİNİN TOPRAK DOLGU BARAJ DENGESİNE ETKİLERİ

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Toprak dolgu barajların yıkılma sebeplerinden birisi şev kaymasıdır. Bu nedenle şev stabilitesi baraj güvenliği için çok önemlidir. Toprak dolgu barajların güvenliğini artırmak için bazı önlemler vardır. Bunlardan birisi, memba ya da mansap şevine palye inşa etmektir. Bu çalışmada palye özelliklerinin baraj stabilitesi üzerindeki etkileri bir vaka çalışmasıyla araştırılmıştır. Farklı palye yükseklikleri, sayıları ve genişliklerinin Türkiye'deki Hancağız Barajı'nın stabilitesine olan etkileri üç yazılım kullanılarak analiz edilmiştir. Zamandan bağımsız akım, haznenin ani dolma ve ani çekilme durumları altında şevlerin güvenlik katsayıları, dolgu içindeki sızma akımı miktarı ve boşluk suyu basınçları elde edilmiştir. Sonuçlar palye yüksekliğini, sayısını ya da genişliğini artırmanın, palyenin inşa edildiği şevde daha yüksek güvenlik katsayıları sağladığını göstermiştir. Palye yüksekliğini belirli bir seviyeye kadar artırmak şev stabilitesini artırmıştır. Palye yüksekliğini daha fazla artırmanın daha düşük şev güvenlik katsayısına sebep olduğu ortaya çıkarılmıştır. Bununla birlikte, memba şevindeki palyenin özelliklerini değiştirmenin, mansap şevinin güvenliğini etkilemediği ve bunun tam tersinin de geçerli olduğu saptanmıştır. Bunların yanında palye geometrisinin dolgu içindeki sızma akımına ve boşluk suyu basınçlarına çok az etkidiği görülmüştür.

Anahtar Kelimeler: Toprak dolgu baraj, palye, sızma analizi, şev stabilitesi analizi, sonlu elemanlar yöntemi

To my family…

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TABLE OF CONTENTS

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

A	Area throughout the boundary
a	Column vector of deformations
B	Gradient matrix
b	Intensity of body force
c	Cohesion, [kPa]
C	Hydraulic conductivity matrix
E	Modulus of elasticity, [kPa]
F_f	Force equilibrium factor of safety
Fk	Chimney drain
F_m	Moment equilibrium factor of safety
F_n	Incremental force
FEM	Finite Element Method
Ft	Aggregate filter
g	Gravitational acceleration, [m/s²]
H	Total head, [m]
h_b	Berm height, [m]
h_d	Dam height, [m]
I	Hydraulic gradient
K	Protective blanket
k	Hydraulic conductivity, [m/day]
k_x	Hydraulic conductivity in horizontal direction, [m/day]
k_y	Hydraulic conductivity in vertical direction, [m/day]
LEM	Limit Equilibrium Method
m_v	Coefficient of volume compressibility, [1/kPa]
N	Interpolating function vector
n_b	Berm number
p	Incremental surface pressure

q	Unit discharge, [$m^3/s/m$]
Q	Flux, [m^3/day]
R	Riprap protection
t	Elapsed time
t_b	Berm width, [m]
t_c	Crest width, [m]
v	Element volume
θ	Volumetric water content
Ø	Angle of friction
θ_s	Saturated water content, [m^3/m^3]
θ_r	Residual water content, [m^3/m^3]
ρ	Mass density, [g/cm^3]
γ	Unit weight, [kN/m^3]
μ	Poisson's ratio

CHAPTER 1

INTRODUCTION

1.1 General

The design of embankment dams requires immense knowledge, skill and experience since embankment materials can exist in an endless variety of dimensions and granulometry. The properties of these materials depend on many factors, such as the degree of saturation and loading conditions (Singh and Varshney 1995). Furthermore, the relation of stress-strain becomes more complicated in earthen embankments.

The failure of embankment dams results in great disaster. One of the reasons of dam failure is the slide of its slopes. Therefore, the stability of slopes is crucial for earth-fill dam safety. Slopes tend to slide under some loading and hydraulic conditions, such as steady-state seepage, rapid fill and rapid drawdown. To prevent failure, it is required to take all possible precautions. Constructing berm on upstream or downstream slopes of dams is one of the advantageous ways to increase the safety of an earth-fill dam. In this study, the effects of berm properties on dam stability are investigated by examining safety factors, pore water pressures, and seepage rates through the embankment of the dam.

1.2 The Aim and Scope of the Study

The aim of this study is to investigate the effects of berm properties on earth-fill dam stability. To fulfill this work, seepage and slope stability analyses are performed by SEEP/W and SLOPE/W software. Also, in order to obtain stress distributions in the embankment, SIGMA/W program is used. SEEP/W and SIGMA/W are finite element based software. In this work, Hancağız Dam, Turkey, which is an earth-fill type, is used for the analyses. This embankment dam has only one berm and it is on the upstream face. In different cases, the properties of the berm on the upstream face are varied. In the first stage, analyses are conducted by altering the original berm height which is 17 m, to 10 m, 24 m, 31 m and 38 m. In the second stage, berm number is varied by adding new berms on upstream face and then by removing the existing berm. In this stage, no berm, one berm, two berms, and three berms cases are analyzed. In the third stage, the original berm width, which is 7 m, is varied to 3 m, 10 m and 15 m. These cases are considered for steady-state seepage, rapid drawdown, and rapid fill conditions. Normally, Hancağız Dam has no berm on its downstream face, but to investigate the effects of a downstream berm, a new berm is added on the downstream face. After adding a berm, the analyses conducted for the upstream berm are repeated for the downstream berm under the same hydraulic conditions, i.e. steady-state seepage, rapid drawdown, and rapid fill. In all analyses, safety factors of both upstream and downstream slopes are determined. The stability behavior of the slopes are also investigated.

1.3 Organization of the Thesis

This thesis is composed of six chapters. In Chapter 1, the aim and scope of the study are explained. In Chapter 2, critical conditions causing failures in earth-fill dams and some significant dam failures in history are stated. In addition, properties of dams having berm in Turkey is presented. In Chapter 3, equations and the methods

used in analyses are given. Chapter 4 gives the variation of pore water pressures, seepage rates and safety factors concerning different berm properties. In Chapter 5, the results of analyses given in the previous chapter, are discussed. Finally, summary and major findings of the study are provided in Chapter 6.

CHAPTER 2

REVIEW OF SLOPE STABILITY AND DAM SAFETY

This chapter deals with the review of some critical conditions leading to failure of earth-fill dams. The role of berm application is discussed with reference to related literature and the application practice in Turkey is provided.

2.1 Critical Conditions Causing Failures in Earth-Fill Dams

There are three critical conditions for earth-fill dam stability. These are end of construction, steady-state seepage condition, and rapid drawdown condition (ASCE 1989).

2.1.1 End of Construction

In the construction of a dam, the material placed in the core of the embankment should have a specified moisture content for the best compaction. As the construction progresses, increased load results more compaction of the material and consequently pore water pressure increases beyond preferred limits. This case can be sensitive for upstream or downstream slope stability of the dam at the end of the construction. As a matter of fact that, pore water pressure can play a critical role in the safety of the dam.

2.1.2 Steady-State Seepage Condition

After reservoir water has been at the maximum level for sufficiently long time, pore water pressure develops below the phreatic line in the embankment and steady-state seepage condition occurs. A seepage face may develop in this condition on the downstream face. The fine soil particles may be washed from this part and this may initiate piping failure.

2.1.3 Rapid Drawdown Condition

If the water in the reservoir lowers too quickly, then drainage of upstream slope might not meet the required evacuation rate. Therefore, the material in the embankment remains saturated with high pore water pressures. Since embankment cannot dissipate pore water pressure as quickly as rapid drawdown rate, it causes seepage towards both upstream and downstream faces of the dam. This condition is critical for only upstream slope, because when the reservoir is full and steady-state seepage condition is valid, the upstream slope becomes more saturated than the downstream slope. Consequently, after rapid drawdown takes place, pore water pressures in upstream slope is higher than in downstream slope. Furthermore, after rapid drawdown occurs, the stabilizing effect of the water is lost on the upstream face. So this condition is critical for only upstream slope.

2.2 Safety Factor for Embankment Slopes

The safety factor means the ratio of resisting forces to driving forces or the ratio of resisting moments to driving moments (Abramson et al. 2002). There are different suggested minimum factor of safety values for different loading conditions. Tables 2-1 and 2-2 show minimum recommended safety factors for rapid drawdown and steady-state seepage conditions.

Table 2-1: Recommended minimum values of safety factor for rapid drawdown condition

Required Minimum Safety Factors for Rapid Drawdown Condition	
United States Army Corps of Engineers (USACE 2003)	1.3
Federal Energy Regulatory Commission (FERC 1991)	1.1
United States Bureau of Reclamation (USBR 1987)	1.3
California Department of Water Resources (Persson 1997)	1.25
United States Department of Agriculture (NRCS 2005)	1.2
American Society of Civil Engineers (ASCE 1989)	1.3

Table 2-2: Recommended minimum values of safety factor for steady-state seepage condition.

Required Minimum Safety Factors for Steady-State Seepage Condition	
United States Army Corps of Engineers (USACE 2003)	1.5
Federal Energy Regulatory Commission (FERC 1991)	1.5
United States Bureau of Reclamation (USBR 1987)	1.5
California Department of Water Resources (Persson 1997)	1.5
United States Department of Agriculture (NRCS 2005)	1.5
American Society of Civil Engineers (ASCE 1989)	1.5

2.3 Failure of Earth-fill Dams

Foster et al. (2000) worked on the statistical analysis of embankment dam failures. According to their study, dam failure due to sliding is only 4% of embankment failures and slide of upstream slope is very rare. Statistical analysis also showed that geological factors like foundation properties do not have significant effect on failure of embankment dams. Those dams which do not have appropriate control of pore water pressure and seepage encounter more stability problems than others.

Singh and Varshney (1995) mentioned some important dam failures due to rapid fill in history. Teton Dam in USA failed during a spring run-off. A rapid fill rate of 1.2 m/day occurred in May, 1976. It caused water flowing at two places from the downstream slope of the dam. Seepage increased rapidly with growing erosion in the dam body and eventually crest of the dam shattered which then caused a complete failure. In this incident, fourteen people and thousands of livestock died. It was estimated that, property worth of $400 million was lost (Singh and Varshney 1995). In India, Panshet Dam failed in 1961 because of heavy rainfall of monsoons. The water level increased by 9 m in one day. After water level remained the same during next four days, another rapid fill occurred which had a rate of 2 m/day. This incident caused breaking of the conduit in dam body, leakage at the downstream toe, subsidence of crest with the embankment, and the complete failure (Singh and Varshney 1995). Sampna Dam failed in India in 1961 due to rapid drawdown. A rapid drawdown rate of 7 m/day observed in the reservoir. The upstream slope with half of the crest, slipped because of fast the decrease in water level (Singh and Varshney 1995). Belle Fourche Dam located in the USA, experienced a rapid drawdown in 1931, more than 20 years after its completion of construction. Reservoir water decreased at an unforeseen drawdown rate, as a consequence, upstream slope slipped (Singh and Varshney 1995). Except for rapid fill and drawdown conditions, there are also dam failures due to steady-state seepage condition. One of them was the failure of Fruit Growers Dam in the USA, in 1937 (Sherard et al. 1963). During its operation, downstream slope slided when the water level was at the maximum elevation. Slided materials closed down the outlet conduit which is supposed to lower the reservoir. Another incident due to steady-state seepage is the failure of Great Western Dam which occurred in 1958. Sliding occurred after the water level in the reservoir had been at the maximum elevation for almost 14 days. Split materials from the embankment, moved into the foundation. As a result, reservoir water passed through the dam body and flowed out to the downstream slope. Due to a very rapid release of water (approximately 85 m depth of water is released in few days) from the Gökdere Köprü Dam

reservoir in Turkey, the gate of the bottom outlet collapsed, resulting in loss of several lives and serious damage to various types properties.

2.4 Berm Characteristics

In USBR (1987) a berm is defined as “a shelf that breaks the continuity of a slope” (see Figure 2-1). For both the upstream and downstream slope of a dam, berm is considerably useful and it has many advantages with regards to dam safety. Berm can be helpful for controlling erosion by intercepting and diverting rain water on the downstream slope of the dam (Jansen 1983). It is also used for reclamation purpose to make available for a stage to work in construction and it is utilized for maintenance and observation of embankment slopes (USBR 1998). In similar to this situation, a berm usually has 5 to 6 meter width (USBR 2013).

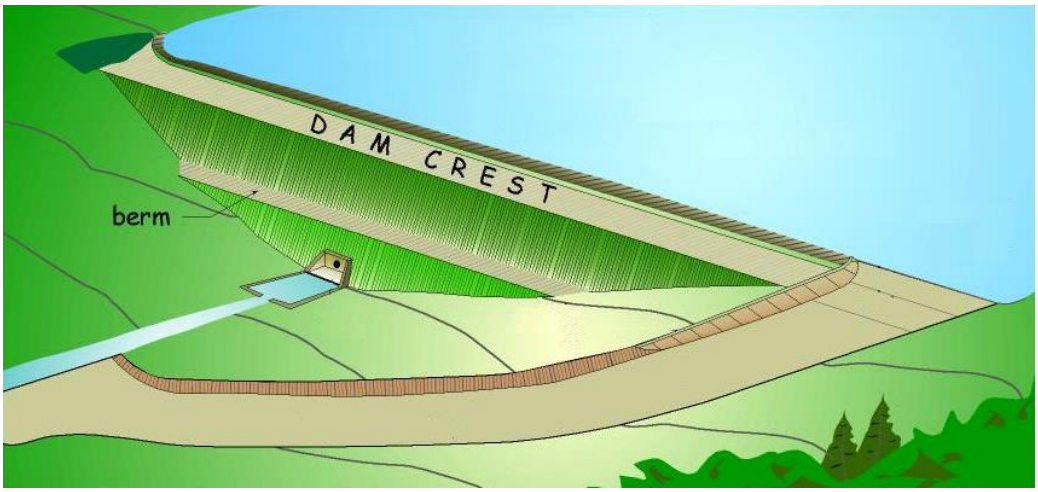


Figure 2-1: Berm on downstream slope of a dam (adopted from water.ohiodnr.gov)

FEMA (2015) states that one of the effective ways for lengthening the seepage path through an embankment is construction of a berm. It extends the seepage path length by enlarging dam body at the foundation. In this way, seepage and instability due to high pore water pressures decrease. Thus safety factors against uplift increases. Furthermore, downstream berm can be utilized as seepage-control measures if filters

and drains are incorporated into the design (USBR 2014). If construction of upstream impervious blanket or cut off wall is too costly, then a downstream seepage berm can be useful to decrease uplift pressures in the pervious foundation at the toe of the dam. Other seepage control measures like toe trench drains or relief wells, are supposed to be constructed with the downstream berm (USACE 2004).

A berm provides resistance to sliding of slopes. Therefore, the stability of the embankment increases (USACE 1986). Toe berm can be used to increase the stability of dam embankments resting on plastic foundations. Material which is obtained from the excavation of plastic foundation, is not favorable for structural zones of a dam. Instead of this, such excavated material is suitable for toe berm of the dam. Constructing berm at the toe, can also quite reduce the potential to trigger liquefaction (USSD 2011). The berm is a stabilizing mass for dams which are on weak foundations (USBR 2012). Since, in case where safety factor is low, the addition of the berm can hinder downstream movements of the slope.

The waste berm is useful for upstream slope protection and also to make contribution to the stability of upstream and downstream embankment slopes. If the material which is not suitable for zones of embankment is obtained from excavation or borrow area stripping, then this material can be used for the construction of waste berm (USACE 2004).

There are various recommendations for determination of berm dimensions in a dam. Justin (1947) says that dams which are higher than 10 m, should have berm at the downstream slope and their berms must be 2 to 6 m wide. When considering high dams, berms should be located for each 9 m difference in height.

2.5 Literature Review for Berm Application

A large number of researchers have investigated benefits of berms on dam stability. Chin (2005) presented some ground improvement methods for embankments which

are constructed over soft clay. One of the ground treatment techniques suggested in that study was berm construction. It resulted that building counterweight berms increase the stability of slopes since it extends the length of potential slip surfaces in soils. It was also found that the weight of the berm compensates disturbing moment on the potential slip surfaces in slopes. Bartsch and Nilsson (2007) proposed the use of a toe-berm made of coarse materials on downstream slopes of embankment dams to increase the seepage capacity and the stability. It was stated that the downstream slope of the embankment should have a mild slope and be composed of coarse materials to prevent sliding during excessive seepage which causes high pore water pressures. Wesley (2011) investigated the factors affecting the slope stability of embankment dams made of residual soils. In the study, berms found to have no remarkable effects on the stability of the slope. It was stated that berms even might decrease the stability since water is prone to impound on the berms, which may result in much more infiltration into the slope. However, it was also indicated that berms might be useful in decreasing the possibility of erosion and providing access for the maintenance of the slope. Kale et al. (2015) conducted stability analysis of Bembla Dam, an earthen dam located in India. The gravitational forces, seepage, erosion of slopes, rapid drawdown of the reservoir, and earthquakes were stated to be the main factors triggering the instability of the dam body. The factor of safety for the downstream slope of the embankment having a berm assessed for the steady-state seepage with full reservoir case.

Effects of berm width-height-slope on the safety factor of common slopes have been studied for many years. Potts et al. (1993) investigated the effects of soil berms used as supporters for retaining walls. According to the study, the weight of berm was more significant than its geometry. The stability of the wall increased when the weight of the berm increased. Since the weight increases when height increases, greater berm heights resulted in higher stability. Kaniraj and Abdullah (1993) investigated the effects of berms and dry tension cracks on the stability of embankments using limit equilibrium method assuming circular slip surfaces. The

study found that there was no effect of the tension cracks on the stability of slopes with berms. Berms were helpful for stability when failure surface was not at deep. When failure surface passed through extensive depths, berms did not have a significant effect on the factor of safety. The higher values of berm height and width gave a higher factor of safety. When the slope of berm increased the factor of safety decreased. Berm height and width was found to be directly proportional to the factor of safety. However, the slope of the berm was shown to be inversely proportional to the stability of the dam. Araya (2000) investigated the effectiveness of berms installed on embankment dams. An embankment dam with a berm at its downstream toe was analyzed for different widths, heights and slopes of the berm. The safety factor values against sliding were obtained for each case. In addition, the effects of different soil properties of the berm on safety factor were investigated. The results showed that safety factors increased with greater cohesion values and angle of friction. It was also stated that the soil properties of the berm were not as significant as the geometry of the berm, because critical failure surfaces passed beneath the berm through the foundation. When the berm had a greater width and a milder slope, the safety factor increased notably since the moment arm increased. The berms having less height were seen to be more effective than greater height berms in increasing the safety factor of the slopes of the dam. Tatewar and Pawade (2012) performed the stability analysis of Bhimdi earth-fill dam located in India with a height of 21 m. By altering parameters like berm width, different cases were investigated in the study. Berm widths were varied from 3 m to 6 m, and safety factors were obtained for each case. It was obtained that safety factors of slopes increased with the increase of the berm width. Liu et al. (2012) studied various excavation methods and measures to decrease ground deformations by constructing berms in the vicinity, which had 6 m depth and 38 m width. To strengthen the excavation pit, they used berms with different widths, such as 6 m, 3 m and 0 m. For the case in which there is no berm, the maximum settlement happened in excavation pit and when there was a berm having 6 m width, the settlement diminished dramatically. The deformations considerably diminished when berm

width increased. It was found that the use of berm for ground improvement could decrease displacements to half of that of the case without a berm. Toromanović et al. (2016) investigated various measures to provide sufficient stability and performance of a dam in Sweden. One of the measures they proposed, was constructing berm at downstream of the embankment to divert seepage without erosion occurring at the dam toe. In the study, the planned berm was constructed in five steps and at each step the berm height increased. Analyses results showed that the safety factor of the downstream slope increased with every added step of the berm. It was stated that the factor of safety of the slopes of the dam is directly proportional to the berm height. Yegian and Lasalvia (1984) carried out a study, which was about the failure of an embankment during its construction on a soft clay ground. They utilized field and laboratory data in slope stability analysis. This study showed that undrained deformations caused cracks in the core of dam and this situation decreased the shearing resistance of the dam which then resulted in a failure. According to the study, the embankment with long berms having a width of 13 m is more substantial than a rigid compressed embankment. Step by step construction provided enough time for consolidation of the clay foundation. Therefore, shear strength increased, and long berms existing on both sides of the dam body ensured an increased stability. Taft et al. (1999) issued a fact sheet about upstream slope protection for dam safety. According to the report, the wave action in a reservoir caused erosion at the upstream slope of dam body. The repetitive waves eroded the embankment dam and washed the upstream face by generating a breach. A slope protection was recommended to be executed to preserve the upstream slope against wave erosion. The upstream face of the dam was stated to be conserved by vegetative protection combined with a berm. The vegetated berms were expressed to break up the effects of the wave and conserve the upstream slope against erosion. Berms stated to be built at the normal pool level and with a minimum width of 6 m. Sadeghpour et al. (2008) investigated causes of instabilities at Vanyar Dam constructed in Tabriz, Iran. The study proposed some methods to increase the stability of the spillway slope which is on the left side of the dam body.

The study showed that rainfall penetration, weathering, freezing-melting cycles increases in height-caused instabilities in the slope. One of the recommendations made to increase the stability of the slope, having a total height of 140 m, was the construction of berms. A berm, having 4 m to 5 m width and 10 meter high was advised to be constructed. Lonie et al. (2013) investigated a design option that satisfies the necessities for the safety of Maroon Dam, which is a 47 m high zoned earth-fill dam. In various options for the improvement of the stability, they ended up with a two-staged upgrade approach, which consists of a 30 m wide berm in the first stage and a 47 m wide berm in the second stage. Murthy et al. (2013) studied optimal designs of earth-fill dams by specifying berm widths, heights, and slopes. In the study, the main constraints of the objective function were the cost of the construction and the safety factor. In the study, the optimum sizes for berms on the upstream slope were found to be 4.5 m height and 3 m width; for berms on the downstream slope the sizes were 3 m height, 8 m width. Both of the berms had the same 1V:2H slope. Aminjavaheri and Karami (2014) analyzed the stability of Ghoocham non-homogenous earth-fill dam, located in Iran, by using limit equilibrium method. Spencer method was used in calculation of the safety factors. The study proposed methods to increase the safety of the dam. A berm with 13 m height and 78 m width was used at the downstream slope to improve the dam stability. The berm was shown to increase the stability of the dam by %65.

Effect of a number of berms on the safety factor of the dam, has been investigated by some researchers. Song et al. (2011) studied the influences of berm numbers on the stability of tailing dams. The study showed that the number of berms had a significant effect on the safety factor. It was resulted that number of berms significantly affects the safety factor of dams having less than seven berms. When the number of berms increased from two to seven, the factor of safety decreased. However, if the number of berms was greater than 7, the safety factor was seen to be not affected. As a result, one or two berms were stated to be sufficient to increase the stability of the dam.

2.5.1 Berm Application Practice in Turkey

In the scope of this study, data about dams in Turkey having berms are collected from Bilgi (1990) to investigate the Turkish practice in dams with berms. The dams having one berm on the upstream face of the embankment are listed in Table 2-3. The construction year, embankment type, dam height from thalweg (h_d), crest width (t_c), berm height (h_b) and berm width (t_b) are shown in this table.

Table 2-3: Dams in Turkey having one berm on upstream slope

Dam Name	Construction Year	Type	h_d (m)	t_c (m)	h_b (m)	t_b (m)
Adatepe	1995	Rock-fill	95	12	28	8
Akköy	1967	Rock-fill	41	10	10	7
Alakır	1971	Rock-fill	44	10	15	6
Altınapa	1967	Rock-fill	31	10	12	9
Bakacak	1999	Rock-fill	50	10	15	8
Balçova	1980	Rock-fill	73	10	28	30
Bozkır	1982	Rock-fill	52	10	18	6
Berdan	1984	Earth-fill	42	10	10	7
Büyükorhan	1992	Earth-fill	32	7	7	7
Çamlıgöze	1998	Rock-fill	32	10	21	20
Çatören	1987	Earth-fill	35	10	15	10
Çavdarhisar	1990	Earth-fill	51	10	30	7
Demirdöven	1995	Earth-fill	58	10	10	10
Demirtaş	1983	Rock-fill	45	10	15	25
Erzincan	1997	Earth-fill	75	10	15	10
Gayt	1998	Earth-fill	36	10	20	10
Gazibey	1992	Rock-fill	45	10	17	10
Gelingüllü	1994	Earth-fill	45	10	15	24
Geyik	1988	Rock-fill	39	10	15	10
Güldürcek	1988	Earth-fill	50	10	15	10
Güzelhisar	1982	Rock-fill	86	10	40	17
Hacıhıdır	1995	Rock-fill	42	10	10	10
Hancağız	1989	Earth-fill	45	10	17	7
Karacaören	1990	Earth-fill	85	12	21	10

Table 2-3 (continued)

Dam Name	Construction Year	Type	h_d (m)	t_c (m)	h_b (m)	t_b (m)
Kayalıköy	1979	Rock-fill	69	10	29	10
İvriz	1985	Earth-fill	44	10	14	10
Kesiksuyu	1971	Earth-fill	56	10	18	45
Kartalkaya	1973	Rock-fill	56	10	11	25
Kozlu	1988	Rock-fill	57	10	14	10
Kurtboğazı	1967	Earth-fill	53	10	14	10
Kozan	1972	Rock-fill	78	10	28	7
Kültepe	1983	Earth-fill	47	10	15	47
Mecitözü	1977	Rock-fill	50	12	15	5
Saraydüzü	1995	Earth-fill	58	10	13	10
Sarıbeyler	1985	Earth-fill	35	10	12	6
Selevir	1964	Earth-fill	31	10	10	8
Serban	1995	Earth-fill	30	9	13	10
Söğüt	1983	Earth-fill	20	8	4	5
Suat Uğurlu	1981	Rock-fill	38	10	27	15
Sultansuyu	1994	Earth-fill	60	8	28	20
Süloğlu	1979	Earth-fill	49	10	14	23
Tatlarin	1966	Rock-fill	46	10	25	7
Tayfur	1985	Rock-fill	33	10	10	7
Topçam	1987	Earth-fill	56	10	28	20
Uluborlu	1984	Earth-fill	56	10	18	10
Vezirköprü	1994	Rock-fill	73	10	19	10
Yapraklı	1991	Earth-fill	52	10	16	10
Yayladağ	2000	Rock-fill	44	10	12	7
Yortanlı	1998	Earth-fill	45	10	15	7
Yedikır	1985	Earth-fill	28	8	8	8

In Table 2-3, dam heights vary from 20 m to 106 m but crest widths are generally 10 m regardless of the dam height. This situation is not valid for berm height and berm width. It can be said that, berm dimensions are independent of the dam geometry and those are not related to each other.

The dams of Turkey having one berm on the downstream slope of the embankment are listed in Table 2-4. Construction year, embankment type, dam height (h_d), crest width (t_c), berm height (h_b), and berm width (t_b) are shown in this table.

Table 2-4: Dams in Turkey having one berm on downstream slope

Dam Name	**Construction Year**	**Type**	**h_d (m)**	**t_c (m)**	**h_b (m)**	**t_b (m)**
Akköy	1967	Rock-fill	41	10	26	5
Bakacak	1999	Rock-fill	50	10	13	20
Bayramiç	1997	Earth-fill	56	10	26	60
Berdan	1984	Earth-fill	42	10	10	7
Çamlıgöze	1998	Rock-fill	32	10	12	33
İvriz	1985	Earth-fill	44	10	14	10
Karacaören	1990	Earth-fill	85	12	40	7
Kartalkaya	1973	Rock-fill	56	10	11	25
Kesiksuyu	1971	Earth-fill	56	10	19	20
Kozan	1972	Rock-fill	78	10	28	7
Mecitözü	1977	Rock-fill	50	12	5	5
Suat Uğurlu	1982	Rock-fill	38	10	14	20
Tatlarin	1966	Rock-fill	46	10	22	6
Yedikır	1985	Rock-fill	28	8	8	8

As it can be seen in Table 2-4, dam heights vary from 28 m to 85 m; however crest widths are mostly 10 m. For dams having berms at the downstream slope, it can be said that, whatever the dam height is, crest width is generally 10 m. Besides berm width and height change independent of each other.

A preliminary analysis was carried out to investigate possible relations between berm characteristics and dam height presented in Tables 2-3 and 2-4. However, no robust relations were obtained among these variables. Most of the dams in Tables 2-3 and 2-4 were constructed before the year 2000. It is assumed that berm height, number, and width were mainly determined by experience without extensive computer-based simulations. It is, therefore, assumed that every dam is designed according to its local characteristics regarding material type, availability of construction material, use of berms as transportation purpose, etc.

CHAPTER 3

METHODS USED

3.1 Seepage Modeling

Before conducting slope stability calculations, pore water pressures in embankment have to be determined. Pore water pressures affect the stability of slopes. In an earth-fill dam, pore water pressures exist due to the head difference between the upstream and downstream sides of dam body. High pore water pressure within the earth-fill dam body is one of the related problems of the seepage. In this study, a finite element software, SEEP/W (Geo-Slope Int. Ltd. 2007a) program is used to obtain pore water pressure and seepage rates in an embankment dam under steady-state seepage, rapid fill, and rapid drawdown conditions. This software enables users to analyze complicated seepage problems by using Darcy's Law:

$$q = k.i \tag{3.1}$$

where q is the volumetric flow rate of water, k is hydraulic conductivity, and i is the hydraulic gradient. For the analysis of two dimensional seepage problems, Equation 3.1 is modified and below differential equation is obtained:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial H}{\partial y}\right) + Q = \frac{\partial \theta}{\partial t} \tag{3.2}$$

In Equation 3.2, H is total head, k_x and k_y are hydraulic conductivities in horizontal and vertical directions, respectively, t is time, θ is the volumetric water content, and Q is flux value at applied boundary. In this equation, the difference between the flux incoming and outgoing at a point, is equal to the difference in volumetric water content. SEEP/W conducts analyses as if there is no loading or unloading on the soil body, it assumes constant stress. There are numerical methods to solve Equation 3.2. Finite element method is one of the robust techniques used for this purpose. This method splits the shape of the problem into small cells. It establishes the location of failure surface without making assumptions. Besides it can show deformations under the stresses. If Galerkin method is used in finite element equations, two dimensional seepage equation can be obtained:

$$\tau \int_A ([B^T][C][B]) dA\{H\} + \tau \int_A (\lambda < N >^T < N >) dA\{H\}, t = q\, \tau \int_L (< N >^T) dL \qquad (3.3)$$

In Equation 3.3, B is gradient matrix, C is matrix of hydraulic conductivity, H is the nodal head vector, N is interpolating function vector, q is unit discharge, τ is element thickness, t is elapsed time, λ is storage term, A and L display for addition of an element. The detailed information can be found in Geo-Slope Int. Ltd. (2007a).

By using SEEP/W program, seepage rates, flow velocity, pore water pressures in the embankment, total head, and saturated-unsaturated hydraulic conductivity of soil can be obtained. In order to conduct seepage analysis, saturated water content, hydraulic conductivity, and residual water content values for each material type are needed. By this way, volumetric water content and hydraulic conductivity functions for different soil types can be obtained. In this study, the mesh size of the numerical models of Hancağız Dam is globally selected as 1 m for seepage analyses. Yılmaz (2017) obtained seepage rate and pore water pressures in a hypothetical earth-fill dam by varying mesh sizes. She investigated that mesh sizes has no significant effect on seepage rate and pore water pressures. For this reason, mesh size is determined as 1 m in all analyses. Lastly, boundary conditions are defined at the

upstream and downstream faces of dam under the rapid drawdown, steady-state seepage, and rapid fill conditions. The details of the boundary conditions are provided in the relevant sections.

3.2 Slope Stability Modeling

Generally, there are two methods in slope stability calculation. They are the limit equilibrium method and the finite element method. In order to clarify the strengths and weaknesses of these two methods, a literature review is carried out and presented below.

Ugai and Leshchinsky (1995) made a study to show the difference of results of the limit equilibrium method and the finite element method. In their slope stability analysis, safety factors obtained by the finite element method were higher than those obtained by the limit equilibrium method. Minor differences, up to 7%, were observed in values of the factor of safety. According to Griffiths and Lane (1999) the finite element method is more robust option than the limit equilibrium method in slope stability calculations, and they assert that the finite element method should be more widely used in slope stability analysis. Hammah et al. (2004) stated that limit equilibrium method is the most widely used method to determine safety factors in slope stability analysis. However, in recent years under favor of improvements in the computer hardware, the finite element method has become the useful option in slope stability calculations. Baba et al. (2012) studied on a case study that was related to a railway slope in Morocco. In the study, they used both limit equilibrium and finite element methods in slope stability calculations. The study stated that limit equilibrium method was simpler and required less number of parameters; however, with this technique, the soil behavior and complex situations could not be investigated. On the other hand, by the finite element method, slopes could be analyzed precisely and deformations in soil could be investigated. Matthews et al. (2014) investigated advantages and disadvantages of both methods. They said that, the finite element method was superior to limit equilibrium method; however, the

latter also provides credible results. Both of them are useful for different situations. The finite element method is preferable for analyses of complex geometries with seepage, deformation or hydrological-mechanical behavior issues. On the other hand, for analysis of simple geometries or when limited data are available, the use of the limit equilibrium method can be reasonable.

Rabie (2013) searched differences between the limit equilibrium method and the finite element method in the calculation of safety factors of slopes which were exposed to heavy rainfall condition. In the study, higher safety factors were obtained by the finite element method. The results showed that the limit equilibrium method is more conservative than the finite element method. The study stated that, in slope stability calculations the limit equilibrium method is based on the directions of the forces that affect each slice in the slope. The finite element method gives safety factors naturally from analysis without generating significant shapes like slices in the limit equilibrium method. Kanjanakul and Chub-uppakarn (2013) compared the limit equilibrium method with the finite element method. The study stated that the finite element method provides representative solutions of the progressive failure surfaces in slopes since it considers both stress and strain relationship in the soil. However, the limit equilibrium method takes into consideration only forces and moments in the soil. Gofar and Rahardjo (2017) investigated the stability of saturated and unsaturated slopes exposed to rainfall infiltration. The study stated that, limit equilibrium method assumes the soil as a rigid plastic material. Therefore, it does not take into consideration deformations of the slope caused by stress effects. On the contrary, finite element considers deformations. For this reason, the finite element software, SIGMA/W, was used for the analyses in this thesis.

In the light of above previous studies, the following advantages can be listed as the finite element method over the limit equilibrium method:

1) To establish the location or shape of the failure surface, there is no need to make an assumption.
2) In the finite element method, there is no need for slices. Therefore, assumptions which are made for side forces of slices are not needed.
3) The finite element method shows deformations but the limit equilibrium method cannot.
4) The finite element method can observe the growing failure.

For these reasons, the finite element method is preferred for slope stability analysis in this study. The limit equilibrium method is used only for steady-state seepage condition for comparison purpose of two methods.

3.2.1 Stress Distribution Modeling with Finite Element Method

In this study, stress-deformation analyses are done by using a finite element software, SIGMA/W (Geo-Slope Int. Ltd. 2007c). This program enables to obtain insitu stresses in dam embankment which causes deformations. After calculations are done, obtained stress and pore water pressure values are transferred to SLOPE/W program. In this way, slope stability analyses are performed on a stress-based approach. Its detailed formulation enables to figure out too complex problems in stress-deformation issues. SIGMA/W utilizes the following finite element equation:

$$\int_v [B]^T [C][B] dv\{a\} = b \int_v < N >^T dv + p \int_A < N >^T dA + \{F_n\} \qquad (3.4)$$

In Equation 3.4, B is matrix of strain-displacement, C is constitutive matrix, $\{a\}$ is column vector of horizontal and vertical deformations, $<N>$ is row vector of interpolating functions, A is area throughout the boundary, v is element volume, b is intensity of body force, p is incremental surface pressure and $\{F_n\}$ is incremental force. SIGMA/W calculates stress and strain values for each time step by solving

Equation 3.4. Body forces applied to all elements of the finite element mesh are calculated in SIGMA/W program. Body force in y direction is related with the gravity force which affects on element. SIGMA/W calculates the integral:

$$\gamma_s \int_v (< N >^T)\, dv \tag{3.5}$$

to obtain forces in the y direction. In a similar way, by using force intensity in x direction, b_h, in the same integral, nodal forces in x direction are calculated.

$$b_s \int_v (< N >^T)\, dv \tag{3.6}$$

SIGMA/W deals with three loading types. They are normal and tangential pressure, horizontal and vertical stress, and water pressure. In this thesis, the mesh size of the numerical models of Hancağız Dam is globally selected as 1 m for stress analyses. By performing SIGMA/W analysis, deformation conditions and pore water pressures in dam embankment at different times during varied conditions, such as rapid fill and drawdown conditions, are obtained for computation of safety factor by SLOPE/W.

3.2.2 Limit Equilibrium Method

In this study, for the steady-state seepage condition, both limit equilibrium and finite element methods are used in slope stability calculations for comparison purpose. To obtain safety factor for the upstream and downstream slopes with limit equilibrium method, SLOPE/W (Geo-Slope Int. Ltd. 2007b) program is used.

Basically, there are two types of factor of safeties; moment and force equilibrium factor of safety. Moment equilibrium factor of safety is the ratio of the summation of resisting moments throughout the critical slip surface to the summation of the mobilized moments throughout the critical slip surface. It is shown as:

$$F_m = \frac{\sum (c'\beta R + (N - u\beta)\, R\ \ tan\emptyset')}{\sum Wx - \sum Nf + \sum kWe \pm \sum Dd \pm \sum Aa} \tag{3.7}$$

Force equilibrium factor of safety is the ratio of the summation of resisting forces throughout the critical slip surface to the summation of the mobilized forces throughout the critical slip surface. It is shown as:

$$F_f = \frac{\sum (c'\beta \cos\alpha + (N - u\beta)\ tan\emptyset' \cos\alpha)}{\sum N \sin\alpha + \sum kW - \sum D \cos\omega \pm \sum A} \tag{3.8}$$

In Equations 3.7 and 3.8, c' is cohesion, ∅' is internal friction angle, u is pore water pressure, W is weight of slice, N is normal force on the slice, D is point load, kW is seismic load on the slice, R is moment arm, x is the horizontal distance from slice, e is the vertical distance from slice, d is perpendicular distance from point load, α is perpendicular distance from resultant, ω is angle of the point load from the horizontal, and *A* is the resultant external water forces.

3.2.3 Modeling with GeoStudio

In this study all analyses are conducted by using GeoStudio 2007 software. Firstly sequence of analyses should be determined (see Figure 3-1). SEEP/W, SIGMA/W and SLOPE/W are packages of this software. SEEP/W is used to make seepage analyses. In SEEP/W, analysis type of “steady-state” is utilized to obtain pore water pressure in embankment. SIGMA/W is used to get stress distributions in embankment. Analysis type of “insitu” and “coupled stress/pwp” are used in SIGMA/W. Insitu is for steady-state seepage condition and “coupled stress/pwp” is for transient conditions. SLOPE/W is utilized to make slope stability analyses. In SLOPE/W, analysis type of Sigma/W is used to calculate safety factors of slopes.

By using Polylines in Sketch menu, dam body is drawn (see Figure 3-2). Then regions in dam body are created by selecting Regions in Draw menu. By choosing Materials in Draw menu, materials are created and assigned to different regions in dam body (see Figure 3-3). Hydraulic conductivity and volumetric water content functions are estimated in this part. Materials are also created in SIGMA/W and SLOPE/W by entering required soil properties. By selecting “Boundary Conditions” from “Draw” menu, different boundary conditions are created and assigned for upstream and downstream faces (see Figure 3-4). This procedure is repeated in SIGMA/W by entering required data.

By choosing “Slip Surface” from “Draw” menu, slip surface of upstream slope is defined in SLOPE/W (see Figure 3-5). After problem is defined, firstly analyses in SEEP/W are conducted. Then Insitu (SIGMA/W) takes initial pore water pressure values in the embankment from SEEP/W. After Insitu finishes calculations, “Coupled Stress/PWP” (SIGMA/W) takes initial stress conditions from “Insitu”. By using “Insitu” and “Coupled Stress/PWP”, stress distributions in embankment are obtained. Finally SLOPE/W calculates safety factors by considering pore water pressures and stress conditions in dam body. After calculations are done by GeoStudio 2007, graph of safety factor with respect to time can be drawn (see Figure 3-6). It can be done by selecting Slip Surface from Draw menu.

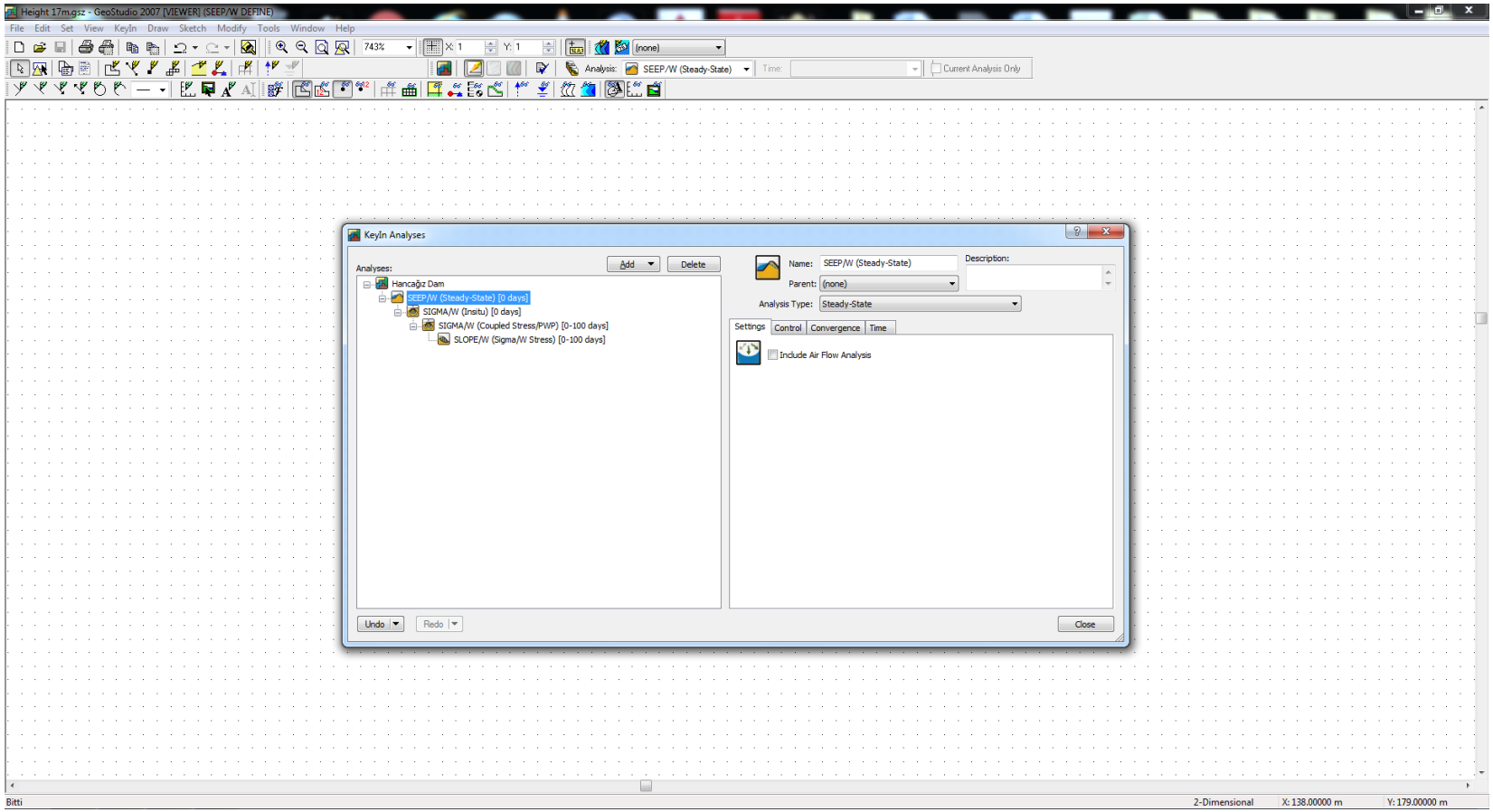


Figure 3-1: KeyIn Analyses in GeoStudio

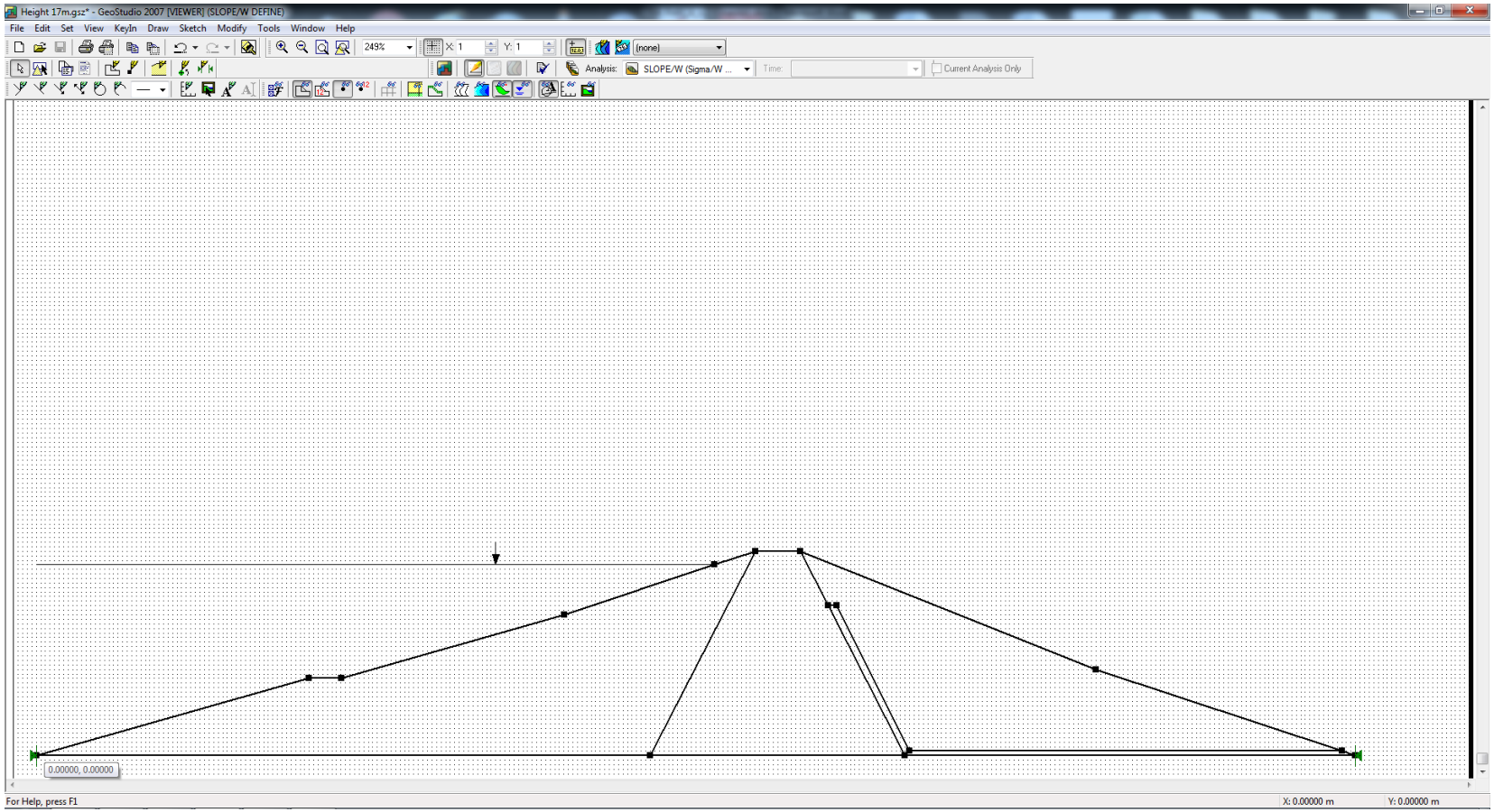


Figure 3-2: Sketching dam body in GeoStudio

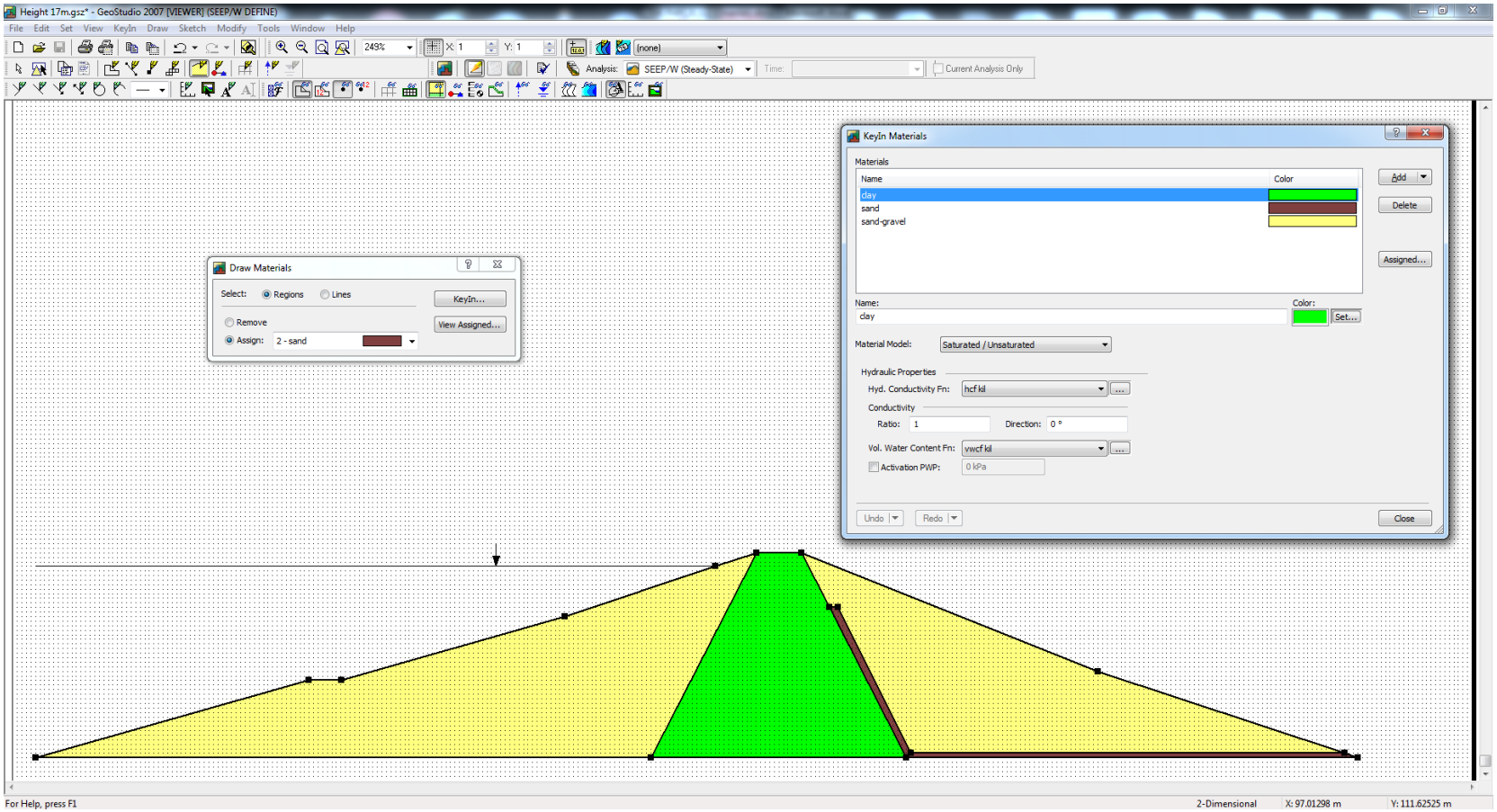


Figure 3-3: Creating materials for different regions in dam body in SEEP/W

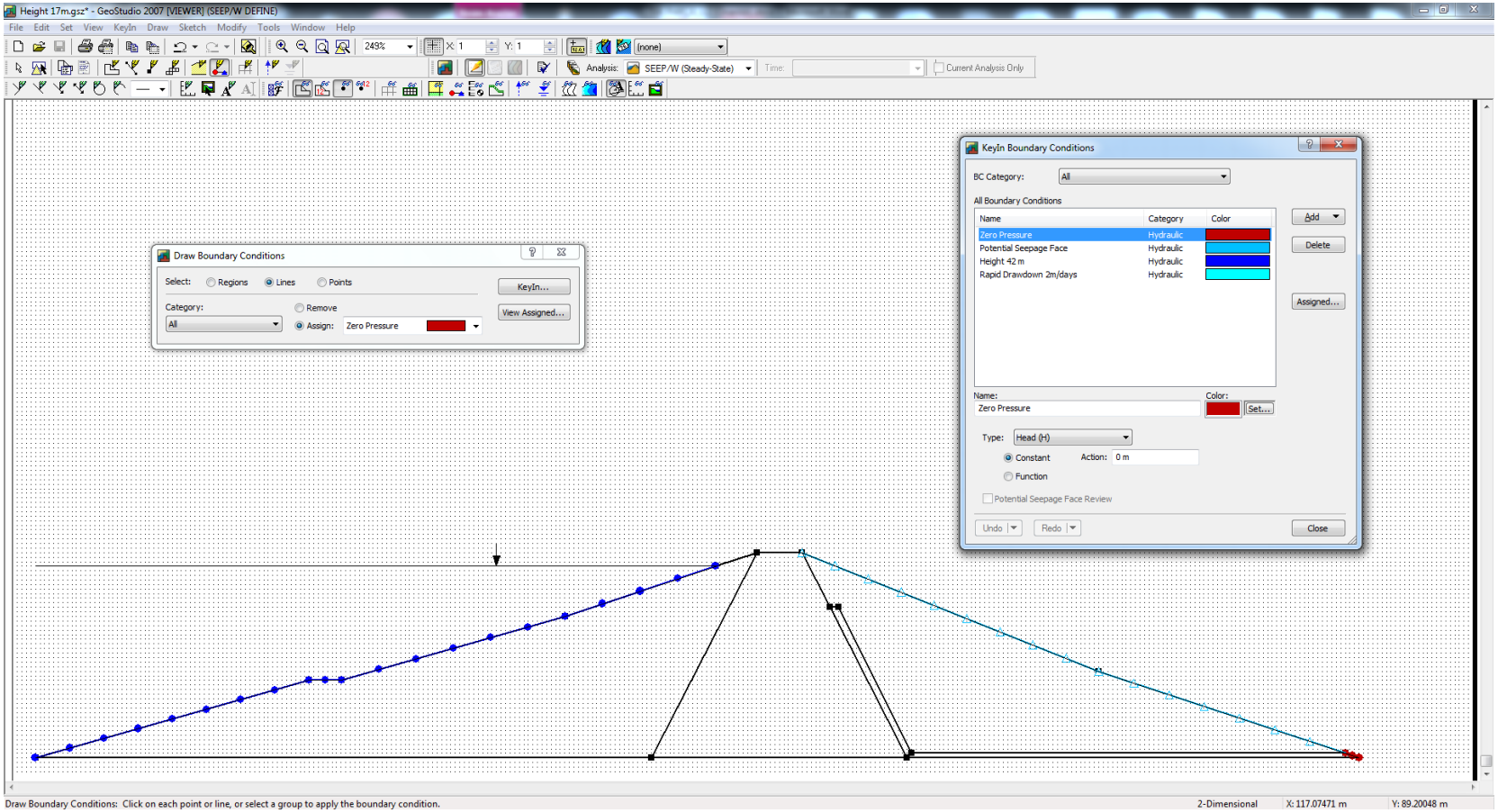


Figure 3-4: Creating boundary conditions for upstream and downstream faces in SEEP/W

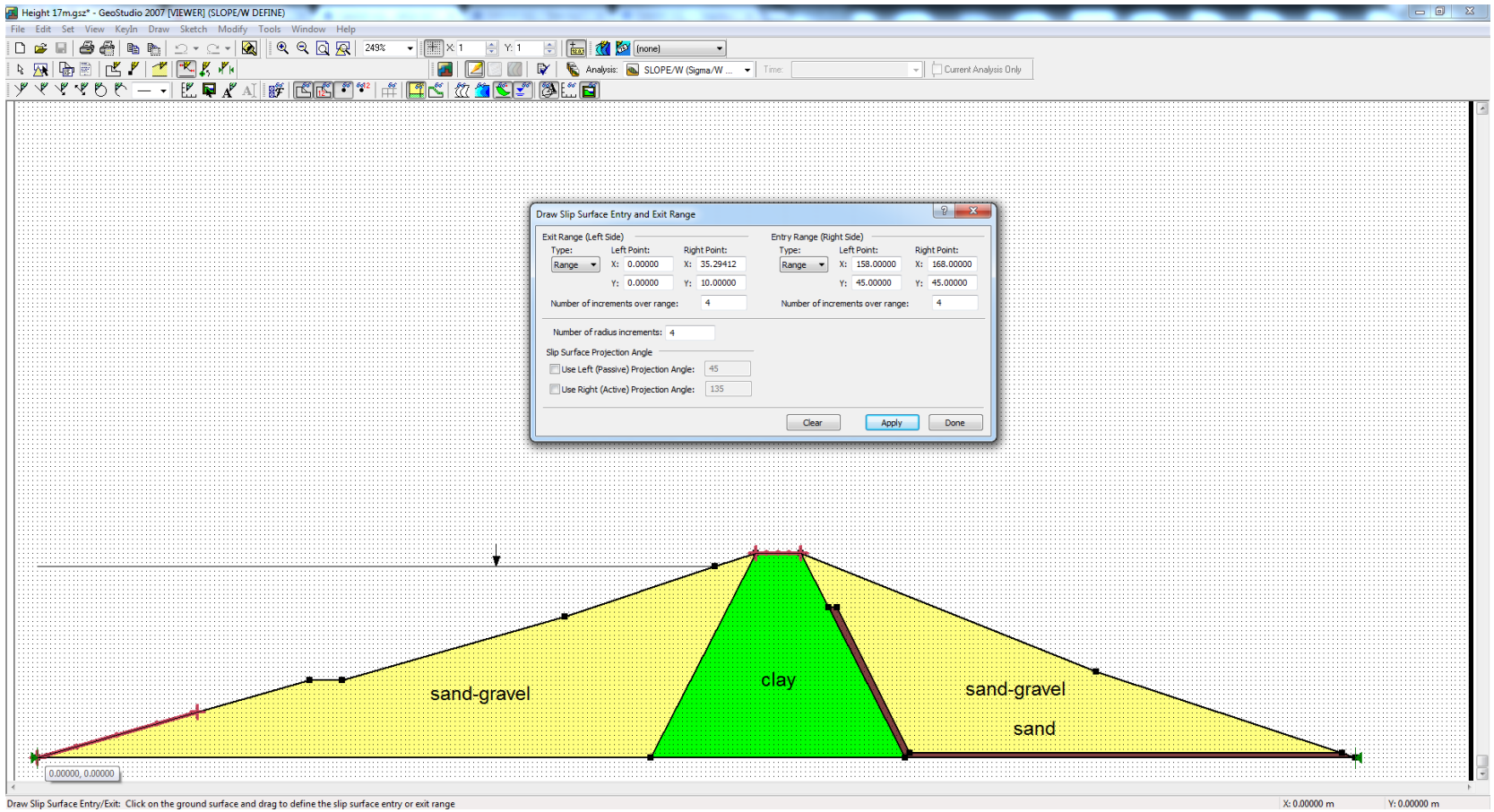


Figure 3-5: Drawing slip surface in SLOPE/W

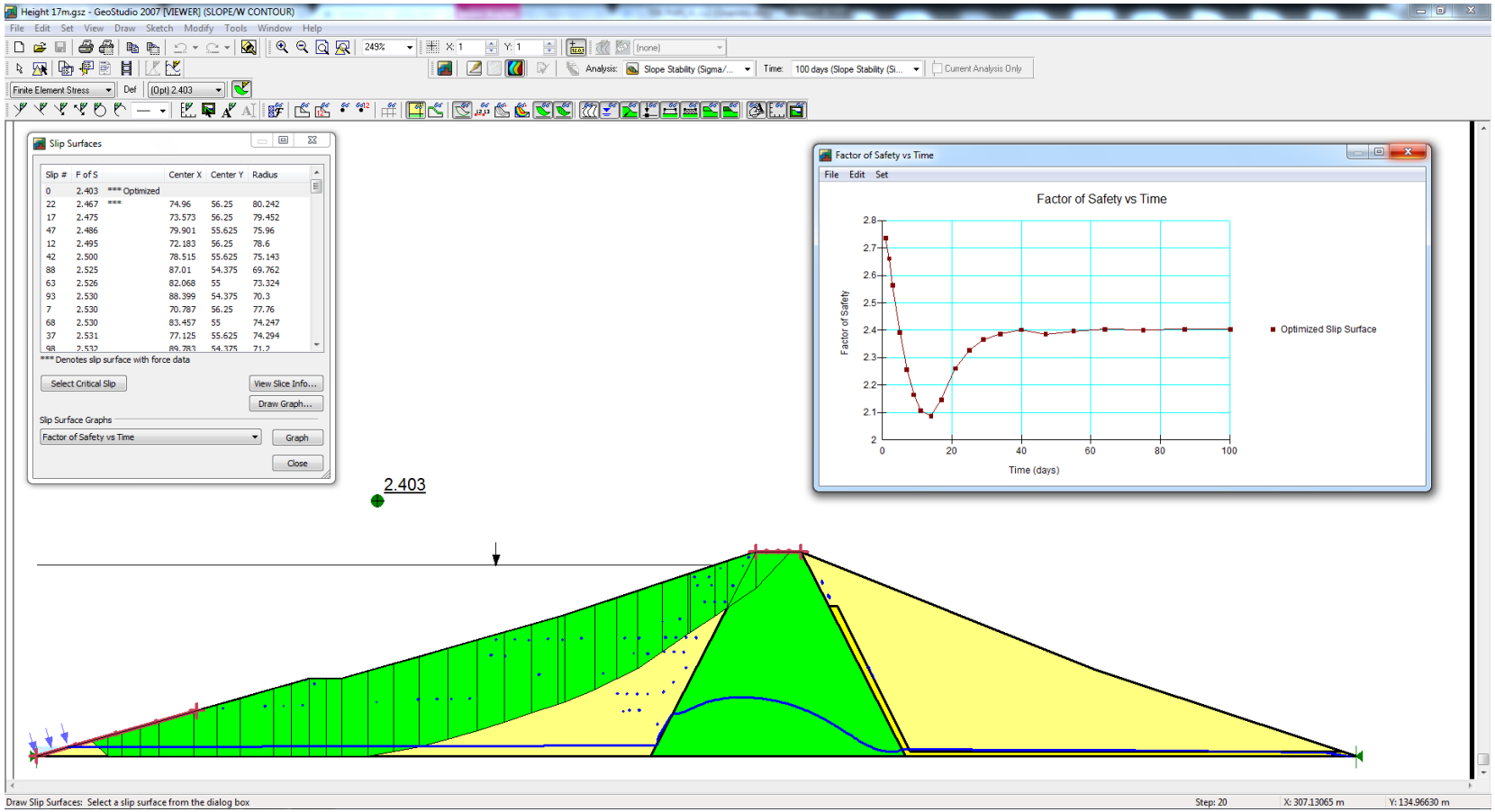


Figure 3-6: Drawing graph of factor of safety with respect to time in SLOPE/W

CHAPTER 4

CASE STUDY: THE EFFECT OF BERMS ON SLOPE STABILITY OF HANCAĞIZ DAM

4.1 Introduction

In this study, Hancağız Dam is selected to investigate the effects of berm properties on stability of dam slopes. The seepage and slope stability analyses are conducted by varying berm properties of the dam under various hydraulic conditions. Figure 4-1 shows the whole analyses conducted for this dam. For steady-state seepage, rapid fill, and rapid drawdown conditions, berm height, number, and width are varied. Figure 4-2 shows cross-sections of different upstream berm cases and Figure 4-3 shows cross-sections of different downstream berm cases considered in this study. In these figures h_b, n_b, and t_b stand for berm height, berm number and berm width, respectively. In order to focus on seepage and stability behavior of the dam body, the foundation is assumed to be impervious. The pore water pressures and seepage rate through the embankment are obtained. Slope stability analysis yielded the safety factors of upstream and downstream slopes of the dam. The results of the overall analyses are presented and discussed in the subsequent sections.

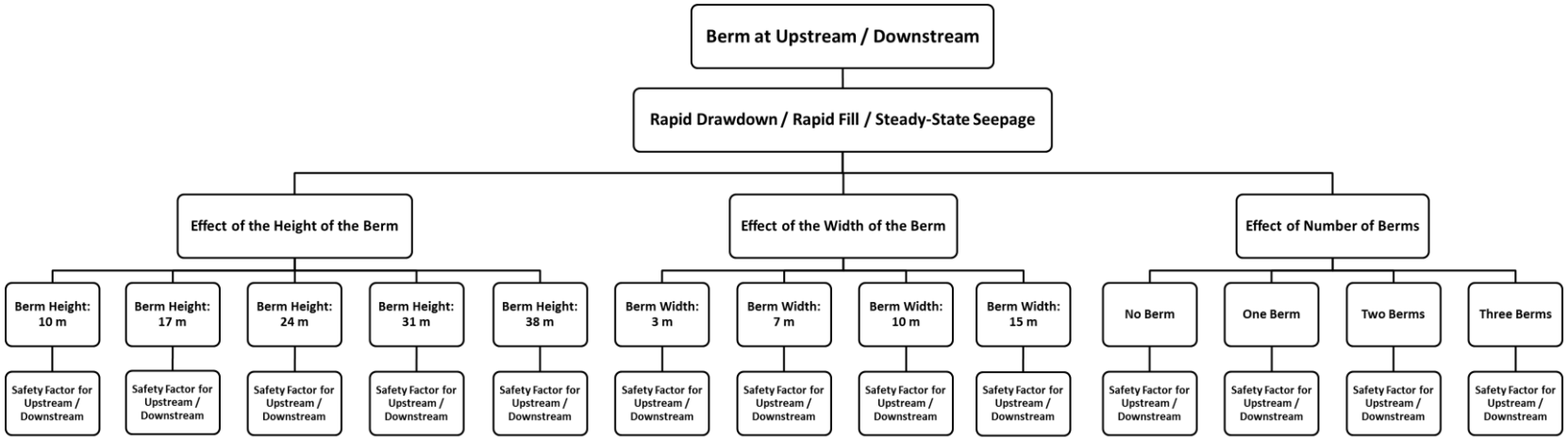


Figure 4-1: Analysis scheme

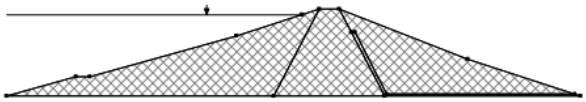
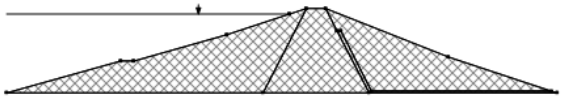
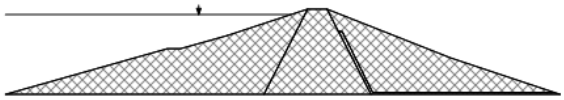
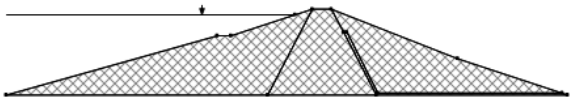
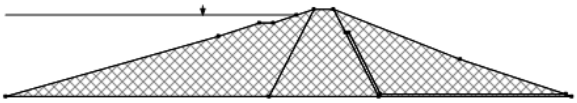
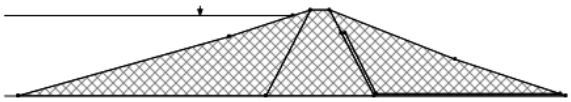
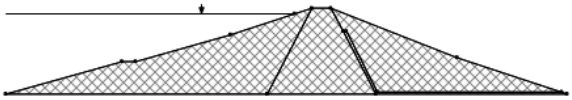
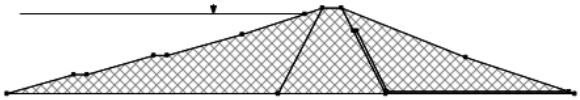
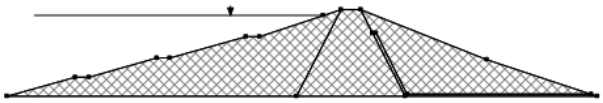
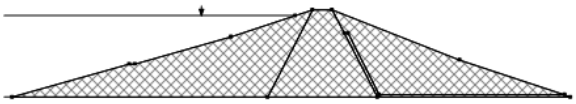
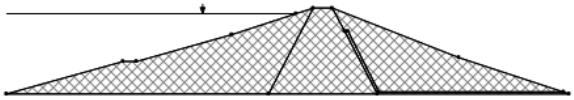
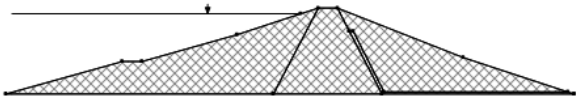
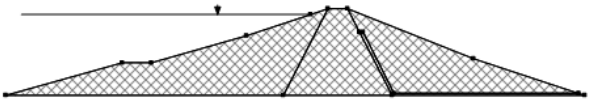
Effect of the Height of the Berm	$h_b = 10$ m	
	$h_b = 17$ m (original case)	
	$h_b = 24$ m	
	$h_b = 31$ m	
	$h_b = 38$ m	
Effect of the Number of the Berm	$n_b = 0$	
	$n_b = 1$ (original case)	
	$n_b = 2$	
	$n_b = 3$	
Effect of the Width of the Berm	$t_b = 3$ m	
	$t_b = 7$ m (original case)	
	$t_b = 10$ m	
	$t_b = 15$ m	

Figure 4-2: Cross-sections of different upstream berm cases

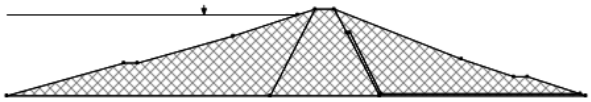
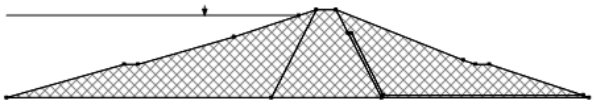
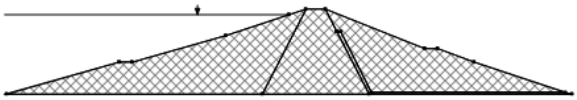
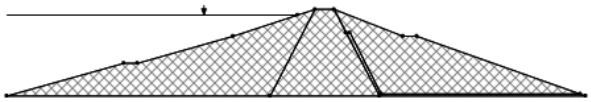
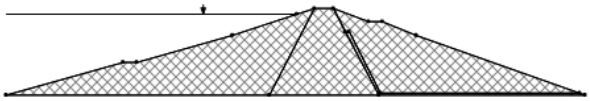
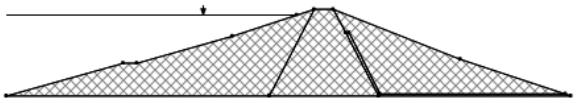
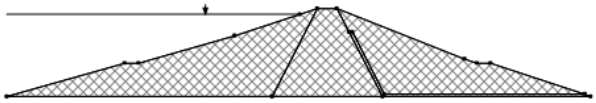
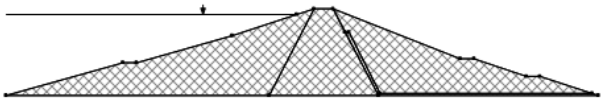
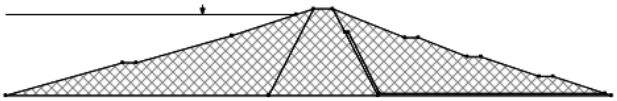
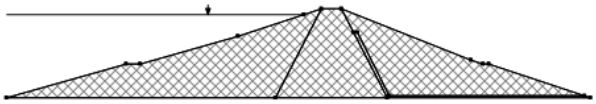
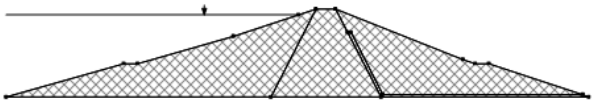
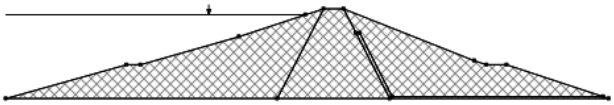
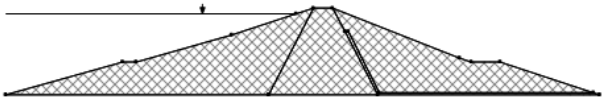
Effect of the Height of the Berm	$h_b = 10$ m	
	$h_b = 17$ m	
	$h_b = 24$ m	
	$h_b = 31$ m	
	$h_b = 38$ m	
Effect of the Number of the Berm	$n_b = 0$ (original case)	
	$n_b = 1$	
	$n_b = 2$	
	$n_b = 3$	
Effect of the Width of the Berm	$t_b = 3$ m	
	$t_b = 7$ m	
	$t_b = 10$ m	
	$t_b = 15$ m	

Figure 4-3: Cross-sections of different downstream berm cases

4.2 Hancağız Dam

4.2.1 General

Hancağız Dam is located in Gaziantep province, Turkey (see Figure 4-4). The construction was completed between 1985 and 1989 years. Following its completion, it has begun to be used for irrigation purpose. Hancağız is a simple zoned earth-fill dam with a clay core. The dam height is 45 m, crest width is 10 m, berm width is 7 m and berm height is 17 m. The volume of the embankment is 3600 dam^3. The upstream and downstream sides have two different slopes. Upstream slopes are 1V:3H and 1V:3.5H, whereas the downstream face is composed of 1V:2.5H and 1V:3H slopes. The cross-sectional view of the dam is provided in Figure 4-5. In the analyses, berm of Hancağız Dam is changed. Height of the berm is increased and decreased by 7 m for different berm heights. Existing berm is removed and then berm number is increased by one for different berm numbers. Berm width is increased and decreased by 50% with respect to the original case.

Figure 4-4: Location of Hancağız Dam in Turkey

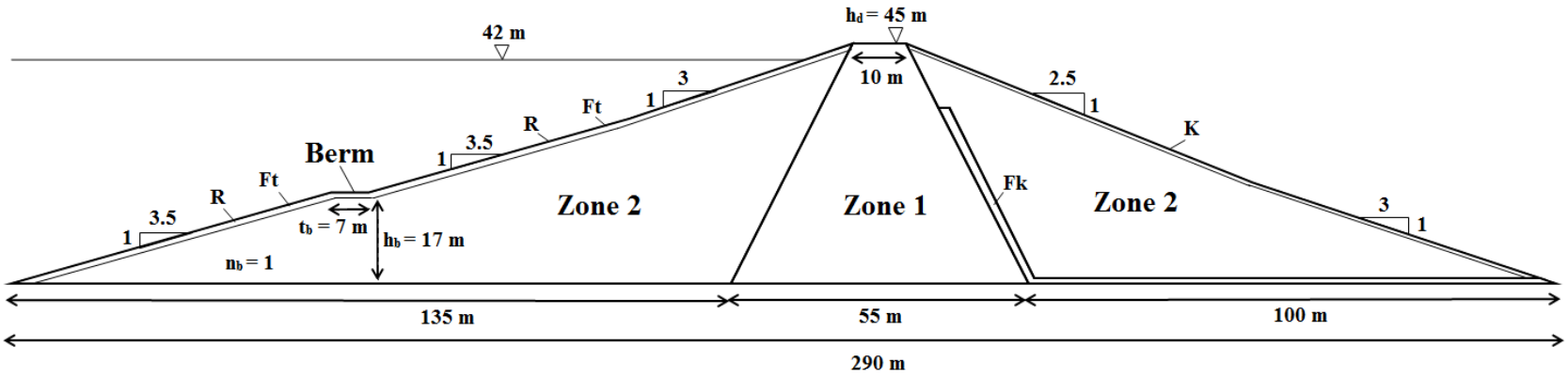


Figure 4-5: Cross Section of Hancağız Dam (Bilgi 1990)

4.2.2 The Material Properties of the Embankment

Hancağız Dam is mainly composed of two zones as presented in Figure 4-5. Zone 1 is the impervious clay core, and Zone 2 is a semi-pervious material made of sand-gravel. In the figure, Fk is the chimney drain which is made of sand filter, Ft is the aggregate filter, R is the riprap protection, and K is the protective blanket. In the analysis of seepage and slope stability, Ft, R and K sections are not considered since they do not affect the behavior of the berm.

The properties of the embankment materials are obtained from various resources. In Table 4-1, parameters to obtain water content function and hydraulic conductivity function are shown. The saturated water content (θ_s), residual water content (θ_r) and hydraulic conductivity (K_s) values are taken from Carsel and Parrish (1988). The coefficient of volume compressibility (m_v) is obtained from Carter and Bentley (1991). These values are used in modeling of seepage in the unsaturated zone.

Table 4-1: Parameters for water content function and hydraulic conductivity function

	Volumetric Water Content Function		**Hydraulic Conductivity Function**	
	$\boldsymbol{\theta_s}$ **(m³/m³)**	$\boldsymbol{m_v}$ **(1/kPa)**	$\boldsymbol{\theta_r}$ **(m³/m³)**	$\boldsymbol{K_s}$ **(m/day)**
Clay (zone 1)	0.38	$5x10^{-5}$	0.068	0.048
Sand	0.43	$5x10^{-6}$	0.045	7
Sand-Gravel (zone 2)	0.50	$5x10^{-7}$	0.02	86

In Table 4-2, parameters used in slope stability analysis are indicated. The unit weight (γ), cohesion (c), and angle of friction ($\varnothing$) values are taken from Bilgi (1990). Modulus of elasticity (E) and Poisson's ratio (μ) are obtained from Bowles (1996).

Table 4-2: Strength parameters of embankment soils of Hancağız Dam

	***E* (kPa)**	**γ (kN/m³)**	**μ**	***c* (kPa)**	**Angle of Friction (°)**
Clay (zone 1)	50,000	19	0.4	59	20
Sand	75,000	20	0.35	0	23
Sand-Gravel (zone 2)	100,000	21	0.3	40	26

4.2.3 Hydraulic Loading Conditions

Hancağız Dam is analyzed under steady-state seepage, rapid fill, and rapid drawdown conditions. In the rapid fill condition, water level is assumed to increase from 2 m to 42 m in 20 days, i.e. 2 m/day. In steady-state seepage condition, water level is assumed to be at 42 m, and in rapid drawdown condition, water level is assumed to decrease from 42 m to 2 m in 20 days (2 m/day). For all analyses, dam is assumed to be constructed on an impermeable foundation.

All earth-fill dams which are in operation, may suffer from steady-state seepage condition. Rapid fill condition may occur mostly in flood detention dams (Çalamak 2014). Common drawdown rates are about 0.1 m/day. On the other hand, drawdown rates of 0.5 m/day are quite significant and higher rates exceeding 1.0 m/day are considered exceptional (Alonso and Pinyol 2009). Since much greater drawdown rates were observed in Gökdere Köprü Dam case, similar rates are also considered in this study since Hancağız Dam is close to the location of Gökdere Köprü Dam.

4.2.4 Variation of the Embankment Volume for Various Berms

Changing the berm height, width or number causes variation in the embankment volume per unit width. Tables 4-3, 4-4, 4-5, 4-6, 4-7 and 4-8 show value of embankment volume per unit width for different berm geometries. As it can be seen from Figure 4-2, any changes in the geometries of upstream and downstream berms, cause a change in the volume of sand-gravel material.

Table 4-3: Total embankment volume, for cross section of different berm height cases, when berm is on the upstream face

h_b (m)	Sand-Gravel Zone (m^2)	Clay Zone (m^2)	Sand Filter Zone (m^2)	Total (m^2)	Increase in the Total Volume (%)
10	4792	1485	150	6427	-0.7%
17	4835			6470	0.0%
24	4886			6521	0.8%
31	4937			6572	1.6%
38	4986			6621	2.3%

Table 4-4: Total embankment volume, for cross section of different berm number cases, when berm is on the upstream face

n_b	Sand-Gravel Zone (m^2)	Clay Zone (m^2)	Sand Filter Zone (m^2)	Total (m^2)	Increase in the Total Volume (%)
0	4720	1485	150	6355	-1.1%
1	4792			6427	0.0%
2	4935			6570	2.2%
3	5152			6787	5.6%

Table 4-5: Total embankment volume, for cross section of different berm width cases, when berm is on the upstream face

t_b (m)	Sand-Gravel Zone (m²)	Clay Zone (m²)	Sand Filter Zone (m²)	Total (m²)	Increase in the Total Volume (%)
3	4767	1485	150	6402	-1.1%
7	4835			6470	0.0%
10	4886			6521	0.8%
15	4971			6606	2.1%

Table 4-6: Total embankment volume, for cross section of different berm height cases, when berm is on the downstream face

h_b (m)	Sand-Gravel Zone (m²)	Clay Zone (m²)	Sand Filter Zone (m²)	Total (m²)	Increase in the Total Volume (%)
0	4835	1485	150	6470	0.0%
10	4898			6533	1.0%
17	4948			6583	1.7%
24	4992			6627	2.4%
31	5100			6735	4.1%
38	5152			6787	4.9%

Table 4-7: Total embankment volume, for cross section of different berm number cases, when berm is on the downstream face

n_b	Sand-Gravel Zone (m²)	Clay Zone (m²)	Sand Filter Zone (m²)	Total (m²)	Increase in the Total Volume (%)
0	4835	1485	150	6470	0.0%
1	4948			6583	1.7%
2	5025			6660	2.9%
3	5225			6860	6.0%

Table 4-8: Total embankment volume, for cross section of different berm width cases, when berm is on the downstream face

t_b (m)	Sand-Gravel Zone (m²)	Clay Zone (m²)	Sand Filter Zone (m²)	Total (m²)	Increase in the Total Volume (%)
0	4835	1485	150	6470	0.0%
3	4883			6518	0.7%
7	4948			6583	1.7%
10	4995			6630	2.5%
15	5075			6710	3.7%

4.3 Slope Stability Behavior of the Embankment for Various Berms

To investigate the effects of berm properties on the dam safety, slope stability analyses are carried out by altering the berm characteristics on the upstream face of Hancağız Dam. Berm height, number, and width are changed in rapid drawdown, steady-state seepage, and rapid fill conditions. In the analyses, safety factors of both of the upstream and downstream slopes are observed. After these works are finished, a new berm is added to the downstream slope of Hancağız Dam and similar analyses are done by making the same changes to the added berm in the same critical loading conditions. Safety of both of the upstream and downstream slopes are also examined.

In this part of the study, the effect of the berm height on safety factor of the upstream slope is investigated for rapid drawdown condition when there is a berm at the upstream. By using stress-based stability analysis technique, factor of safety of the upstream slope is obtained for different berm heights. The results are presented in Figure 4-6.

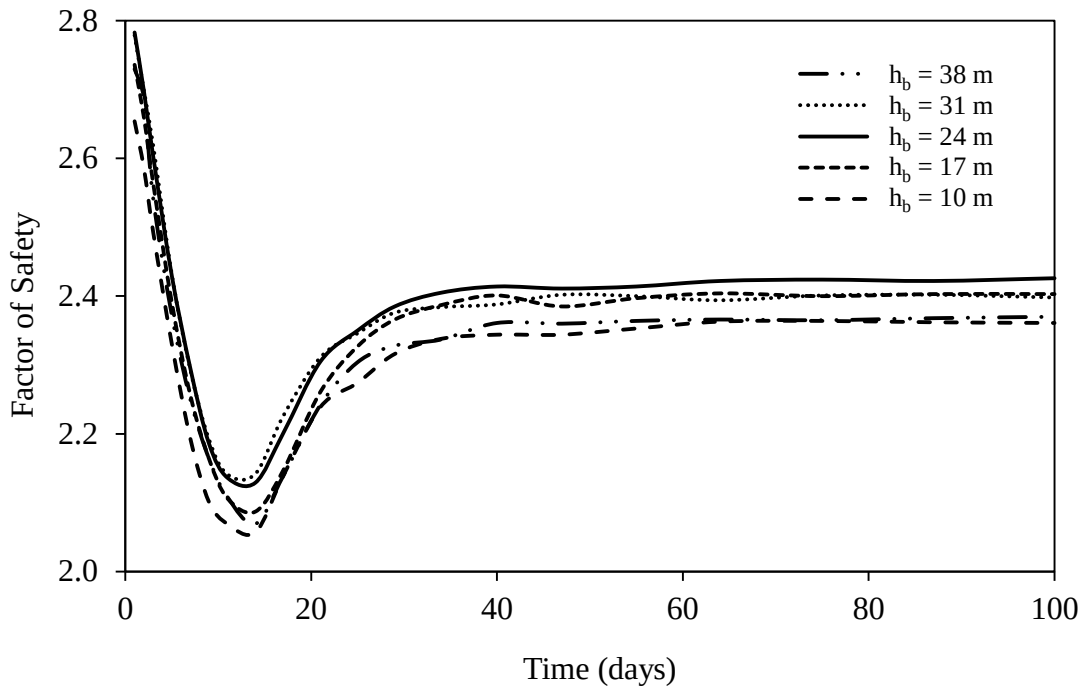


Figure 4-6: Variation of safety factor of upstream slope with respect to time for different upstream berm heights in rapid drawdown condition

As it can be seen in Figure 4-6, safety factor of upstream slope decreases rapidly during 15 days. After safety factor drops to a minimum value, it slightly increases until t=40 days and continues at a constant value until t=100 days. This is because while rapid drawdown occurs, counter-balancing effect of reservoir water against upstream slope failure is diminished (Çalamak et al. 2015). In this period, pore water pressures which trigger slope failure, still exist in dam embankment. When t=15 days, pore water pressure begins to decrease thus the safety factor of upstream slope increases. As soon as pore water is evacuated, safety factor reaches to a constant value. Time-dependent safety factors are greater than the minimum required values (see Table 2-1). In Figure 4-7, cross-section of Hancağız Dam is given and safety factor of upstream slope in rapid drawdown condition is shown. Water level falls to 14 m from 42 m and safety factor becomes 2.08 at critical slip surface when t=14 days. The relation between factor of safety and berm height is shown in Figure 4-8.

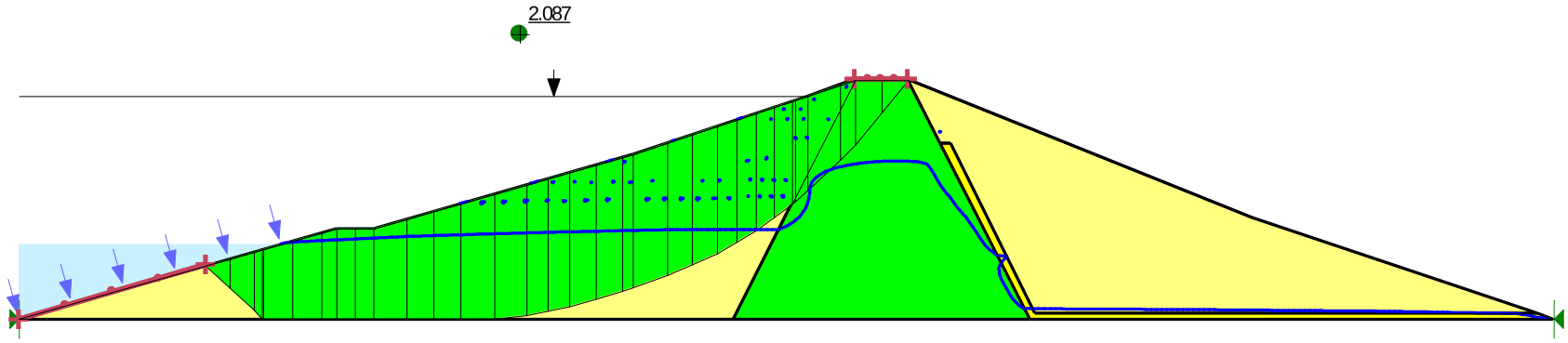


Figure 4-7: Safety factor of upstream slope in rapid drawdown condition and critical slip surface when t=14 days

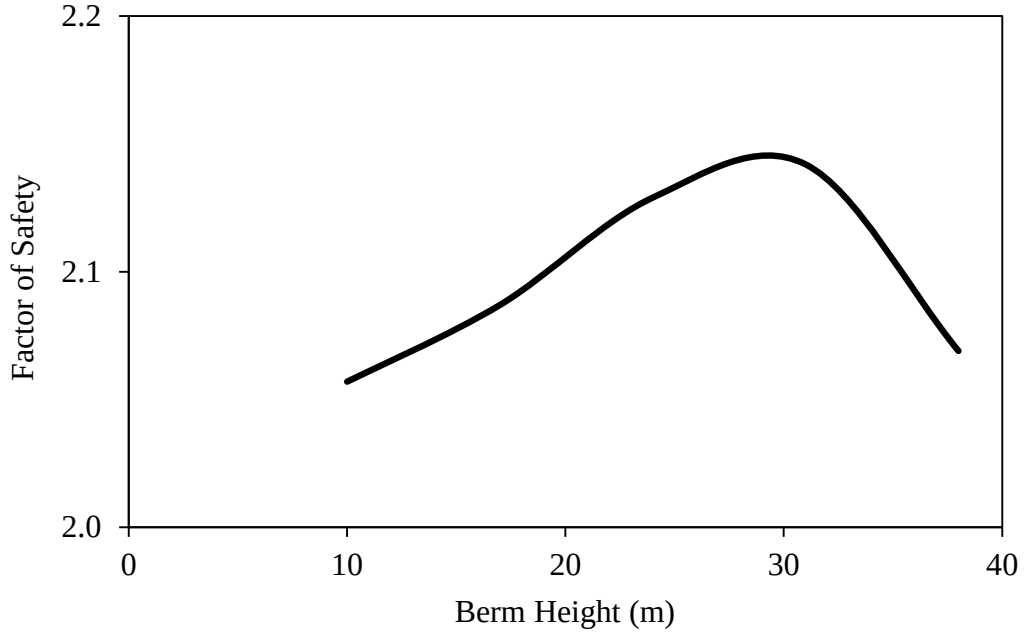


Figure 4-8: Variation of safety factor of upstream slope with respect to upstream berm height in rapid drawdown condition

From Figure 4-8 it can be understood that, in rapid drawdown condition, increasing the upstream berm height provides higher safety factors at the upstream slope of the dam until the ratio of berm height to dam height is 0.66. However, when this ratio is exceeded, increasing the berm height after a certain level causes lower safety factors at the upstream slope.

In Table 4-9, the variation of embankment volume per unit width and safety factors for each different berm height cases are provided. To show the difference in safety factors four different time steps are considered. In this table, the safety factors of the original case of Hancağız Dam, i.e. with a berm having a height of 17 m at the upstream, are indicated with bold numbers. The results showed that it is reasonable to choose the berm height to dam height ratio around 0.55-0.60. This value is 0.37 for the original case of Hancağız Dam corresponding to a safety factor of 2.08, which is satisfactory.

Table 4-9: Variation of safety factor of upstream slope and embankment volume for different upstream berm heights in rapid drawdown condition

Time (days)	**Safety Factor for h_b=17 m**	Safety Factor for h_b=10 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=24 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=31 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=38 m	Difference of Safety Factor	Difference of Volume
1	**2.74**	2.65	-3.1%	-0.7%	2.78	1.7%	0.8%	2.78	1.6%	1.6%	2.73	-0.2%	2.3%
11	**2.11**	2.07	-1.8%		2.14	1.4%		2.14	1.7%		2.11	0.1%	
21	**2.26**	2.24	-1.0%		2.31	1.9%		2.31	2.2%		2.24	-0.8%	
40	**2.40**	2.34	-2.4%		2.41	0.5%		2.39	-0.5%		2.36	-1.7%	

The effect of the number of berms on safety factors of upstream slope is examined for rapid drawdown condition when the berm is at upstream face of the dam. Factor of safety variation is shown in Figure 4-9 for different number of berms.

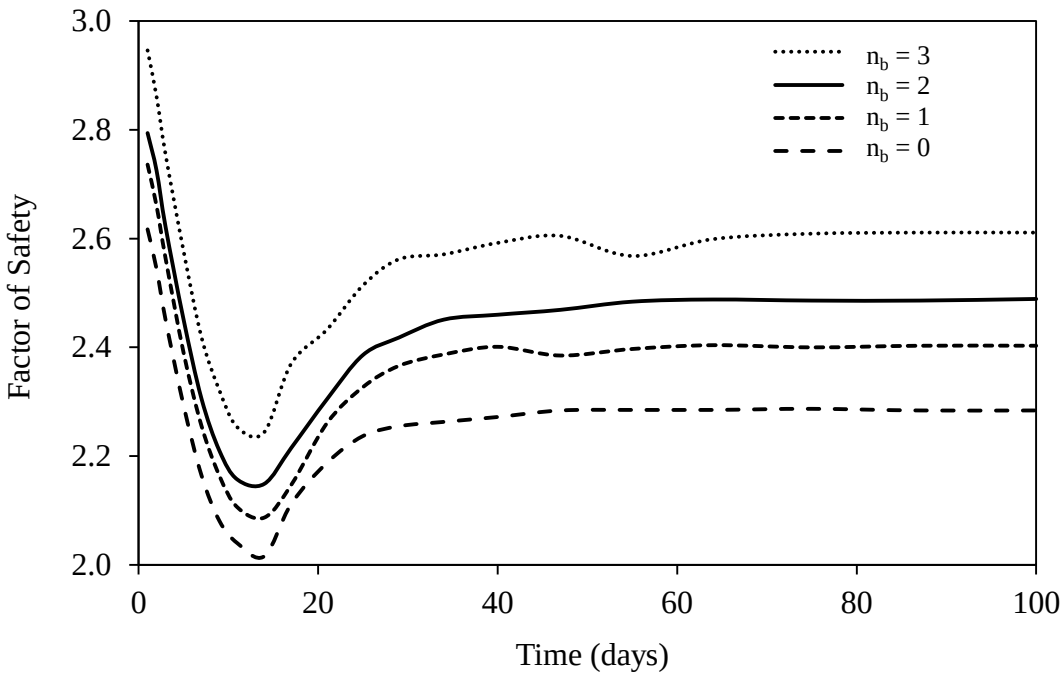


Figure 4-9: Variation of safety factor of upstream slope with respect to time for different upstream berm numbers in rapid drawdown condition

As it is seen in Figure 4-9, it is obvious that increasing the number of the berm at upstream face of the dam, provides higher safety factors of upstream slope of the dam in rapid drawdown condition. Time-dependent safety factors are greater than the minimum required values (see Table 2-1). The variation of embankment volume per unit width and safety factors for each berm number are provided in Table 4-10. To show the difference in safety factors, four different time steps are considered. In this table, the safety factors of the original case of Hancağız Dam, i.e. having one berm at upstream slope, are indicated with bold numbers. When the dam has three berms, the volume of the embankment increases by 5.6%, whereas safety factor increases by 7.6%. When the dam has no berm, volume of embankment decreases by 1.1% with a decrease in safety factor by 4.2%.

Table 4-10: Variation of safety factor of upstream slope and embankment volume for different upstream berm numbers in rapid drawdown condition

Time (days)	**Safety Factor for n_b=1**	Safety Factor for n_b=0	Difference of Safety Factor	Difference of Volume	Safety Factor for n_b=2	Difference of Safety Factor	Difference of Volume	Safety Factor for n_b=3	Difference of Safety Factor	Difference of Volume
1	**2.74**	2.62	-4.5%	-1.1%	2.79	2.1%	2.2%	2.95	7.7%	5.6%
11	**2.11**	2.04	-3.2%		2.16	2.4%		2.25	7.0%	
21	**2.26**	2.19	-3.3%		2.31	1.9%		2.43	7.6%	
40	**2.40**	2.27	-5.7%		2.46	2.5%		2.59	8.0%	

The effect of the width of the upstream berm on safety factor of upstream slope is investigated for various berm widths in rapid drawdown condition. The factor of safety variation is shown in Figure 4-10. As it can be seen from Figure 4-10, it is apparent that increasing the width of the berm at the upstream face of the dam, provides higher safety factors of upstream slope of the dam in rapid drawdown condition.

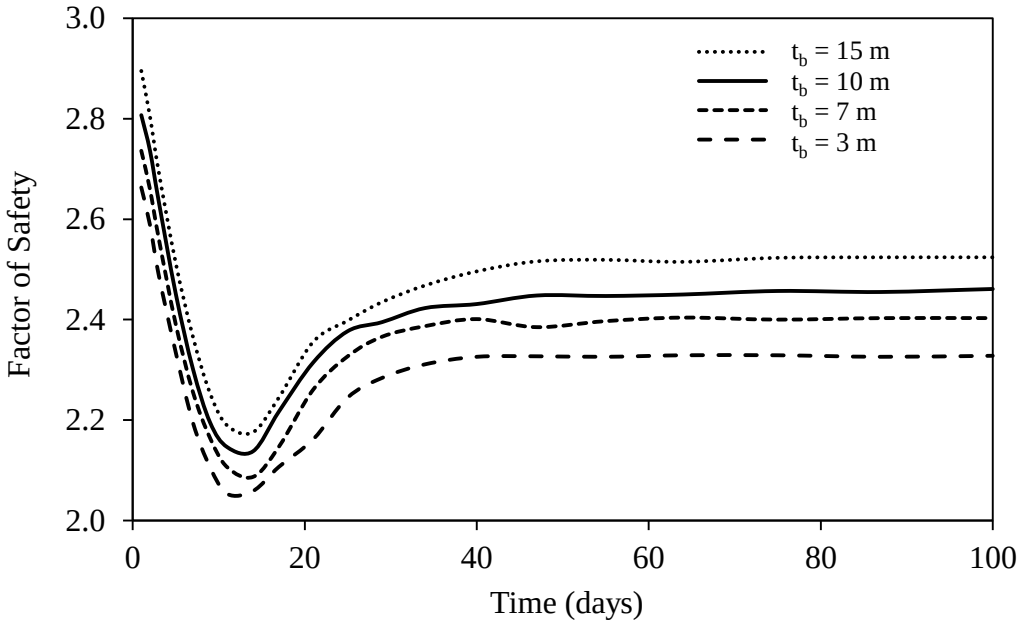


Figure 4-10: Variation of safety factor of upstream slope with respect to time for different upstream berm widths in rapid drawdown condition

In Table 4-11, the variation of embankment volume per unit width and safety factors of each different berm width cases are provided. To show the difference in safety factors four different time steps are considered. In this table, the safety factors of the original case of Hancağız Dam, i.e. with a berm having a width of 7 m at upstream, are indicated with bold numbers. When the berm width is 15 m, volume of embankment increases by 2.1% whereas safety factor increases by 4.5%. When berm width is 3 m, volume of embankment decreases by 1.1% with a decrease in safety factor by 3.3%. Time-dependent safety factors are greater than the minimum required values (see Table 2-1).

Table 4-11: Variation of safety factor of upstream slope and embankment volume for different upstream berm widths in rapid drawdown condition

Time (days)	**Safety Factor for t_b=7 m**	Safety Factor for t_b=3 m	Difference of Safety Factor	Difference of Volume	Safety Factor for t_b=10 m	Difference of Safety Factor	Difference of Volume	Safety Factor for t_b=15 m	Difference of Safety Factor	Difference of Volume
1	**2.74**	2.66	-2.7%	-1.1%	2.81	2.6%	0.8%	2.90	5.8%	2.1%
11	**2.11**	2.05	-2.6%		2.15	1.9%		2.19	3.9%	
21	**2.26**	2.16	-4.6%		2.32	2.4%		2.36	4.2%	
40	**2.40**	2.33	-3.2%		2.43	1.2%		2.50	4.0%	

The effect of the height of the upstream berm on safety factor of the downstream slope is investigated in rapid drawdown condition with variation of berm heights. The variation of factor of safety values are shown in Figure 4-11. As it is seen in Figure 4-11, lines are almost overlapping and they follow the same trend. So, it can be said that in rapid drawdown condition, increasing the height of the berm at the upstream slope of the dam does not affect safety factors of downstream slope. In all cases of different berm height, lines almost remain at a constant level. This is because of the fact that the effects of upstream conditions on pore water pressures in downstream slope is negligible.

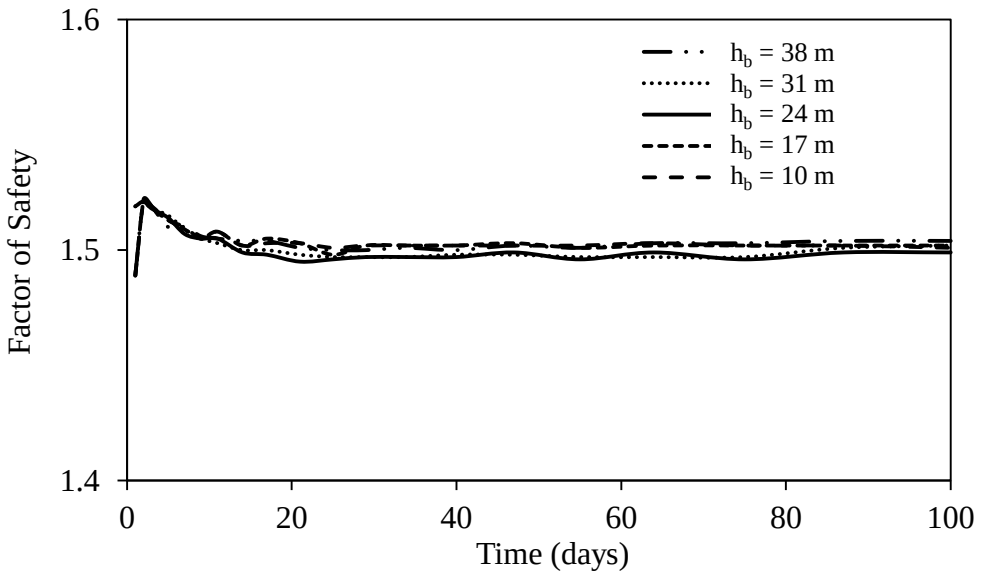


Figure 4-11: Variation of safety factor of downstream slope with respect to time for different upstream berm heights in rapid drawdown condition

In Figure 4-12, cross-section of Hancağız Dam is given and safety factor of the downstream slope in rapid drawdown condition is shown. Water level falls to 14 m from 42 m and safety factor becomes 1.50 at critical slip surface when t=14 days. This value is still acceptable according to the criterion given in Table 2-1. The variation of embankment volume per unit width and safety factors of each different berm height cases are provided in Table 4-12. To show the difference in safety factors four different time steps are considered. In this table, the safety factors of the

reference case of Hancağız Dam, i.e. with a berm having a height of 17 m at the upstream, are indicated with bold numbers. At each increase in the berm height, safety factor values slightly changes although volume of embankment inherently increases. For example when the berm height is 38 m, volume of embankment increases by 2.3% but safety factor decreases by 0.1%. It can be concluded that safety factor of downstream slope does not change while upstream berm height changes.

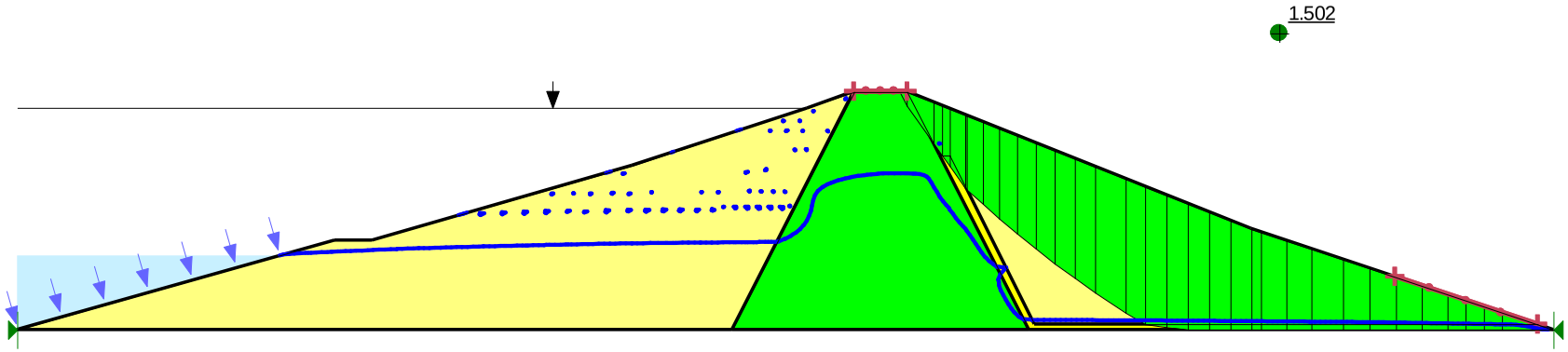


Figure 4-12: Safety factor of downstream slope in rapid drawdown condition and critical slip surface when t=14 days

Table 4-12: Variation of safety factor of downstream slope and embankment volume for different upstream berm heights in rapid drawdown condition

Time (days)	**Safety Factor for h_b=17 m**	Safety Factor for h_b=10 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=24 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=31 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=38 m	Difference of Safety Factor	Difference of Volume
1	**1.49**	1.49	0.0%	-0.7%	1.52	2.0%	0.8%	1.52	2.0%	1.6%	1.49	0.0%	2.3%
11	**1.51**	1.51	0.0%		1.51	-0.2%		1.50	-0.3%		1.51	-0.2%	
21	**1.50**	1.50	0.0%		1.50	-0.5%		1.50	-0.3%		1.50	-0.1%	
40	**1.50**	1.50	0.0%		1.50	-0.3%		1.50	-0.3%		1.50	-0.1%	

In the scope of the study, upstream berm number is changed in rapid drawdown condition. Safety factors of the downstream slope are calculated and they are given in Figure 4-13. The lines nearly remain at the same level in all cases since effects of upstream conditions on pore water pressures of downstream slope is negligible. It can be said that in rapid drawdown condition, increasing the number of the berm at upstream slope of the dam does not affect safety factors of downstream slope.

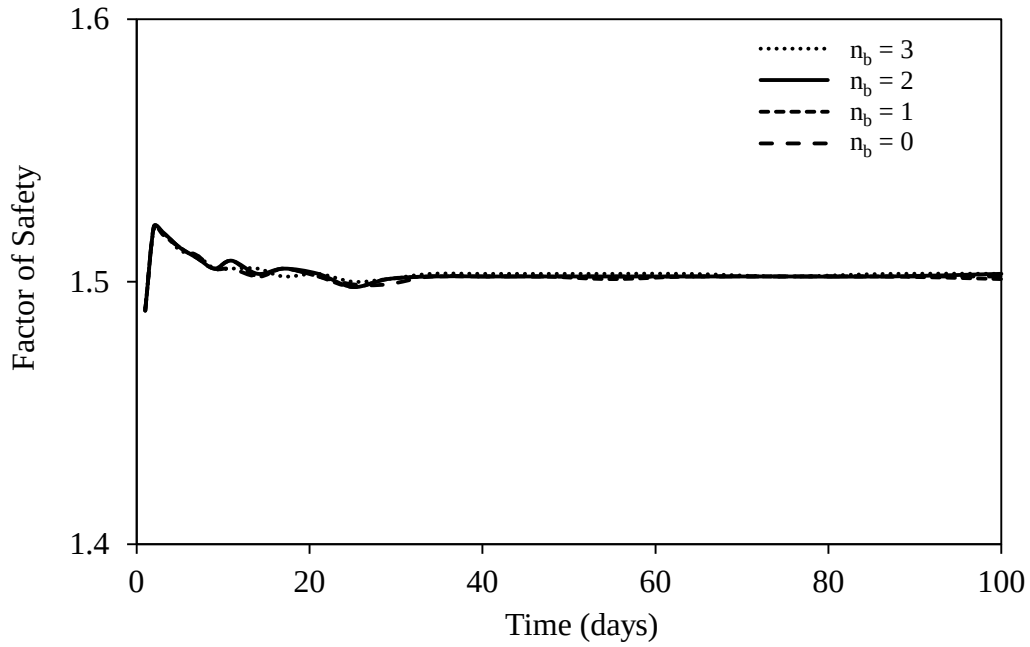


Figure 4-13: Variation of safety factor of downstream slope with respect to time for different upstream berm numbers in rapid drawdown condition

In Table 4-13, the variation of embankment volume per unit width and safety factors of each different berm number cases are provided. In order to show the difference in safety factors four different time steps are considered. In this table, the safety factors of the reference case of Hancağız Dam, i.e. having one berm at upstream, are indicated with bold numbers. At each increase in the berm number, safety factor values do not change whereas the volume of embankment inherently increases. For example when the dam has three upstream berms, the volume of the embankment increases by 5.6% but safety factor of the downstream slope does not change.

Table 4-13: Variation of safety factor of downstream slope and embankment volume for different upstream berm numbers in rapid drawdown condition

Time (days)	**Safety Factor for n_b=1**	Safety Factor for n_b=0	Difference of Safety Factor	Difference of Volume	Safety Factor for n_b=2	Difference of Safety Factor	Difference of Volume	Safety Factor for n_b=3	Difference of Safety Factor	Difference of Volume
1	**1.49**	1.49	0.0%	-1.1%	1.49	0.0%	2.2%	1.49	0.1%	5.6%
11	**1.51**	1.51	-0.2%		1.51	0.0%		1.51	-0.2%	
21	**1.50**	1.50	0.0%		1.50	0.1%		1.50	0.1%	
40	**1.50**	1.50	0.0%		1.50	0.0%		1.50	0.1%	

In order to investigate the effect of berm width on safety factor, the width of the upstream berm is varied. Factor of safety variation is given in Figure 4-14. It is clear from this figure that, in rapid drawdown condition, increasing the width of the berm at the upstream slope of the dam, does not affect the safety factors of the downstream slope since effects of upstream conditions on pore water pressures of downstream slope is negligible.

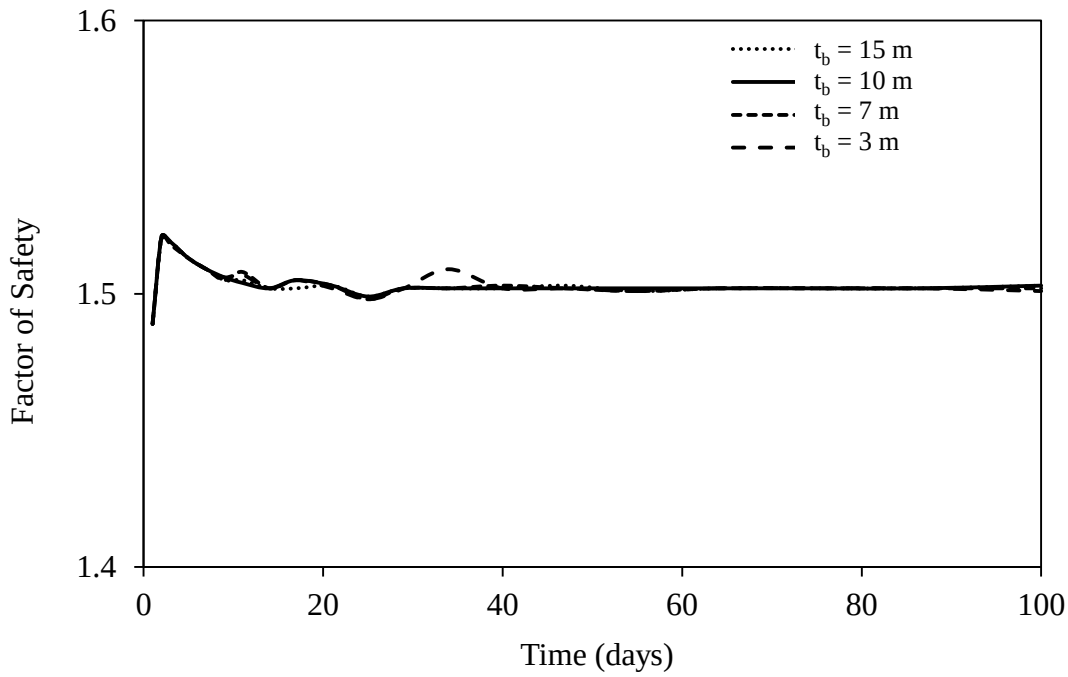


Figure 4-14: Variation of safety factor of downstream slope with respect to time for different upstream berm widths in rapid drawdown condition

In Table 4-14, the variation of embankment volume per unit volume and safety factors of each different berm width cases are provided. To show the difference in safety factors four different time steps are considered. In this table, the safety factors of the reference case of Hancağız Dam, i.e. having berm width of 7 m at upstream, are indicated with bold numbers. At each increase in berm width, the safety factor values do not change whereas the volume of embankment inherently increases. For example, when the berm width is 15 m, the volume of embankment increases by 2.1% but the safety factor is almost constant.

Table 4-14: Variation of safety factor of downstream slope and embankment volume for different upstream berm widths in rapid drawdown condition

Time (days)	**Safety Factor for t_b=7 m**	Safety Factor for t_b=3 m	Difference of Safety Factor	Difference of Volume	Safety Factor for t_b=10 m	Difference of Safety Factor	Difference of Volume	Safety Factor for t_b=15 m	Difference of Safety Factor	Difference of Volume
1	**1.49**	1.49	0.0%	-1.1%	1.49	0.0%	0.8%	1.49	0.0%	2.1%
11	**1.51**	1.51	-0.1%		1.50	-0.3%		1.51	-0.2%	
21	**1.50**	1.50	-0.1%		1.50	0.0%		1.50	0.0%	
40	**1.50**	1.50	-0.1%		1.50	-0.1%		1.50	-0.1%	

In the rapid fill condition, the upstream berm height is also changed. Then safety factors of the upstream slope are obtained. Safety factors are shown in Figure 4-15. In addition to that, factor of safety variation for the upstream slope with respect to the upstream berm height is given in Figure 4-16.

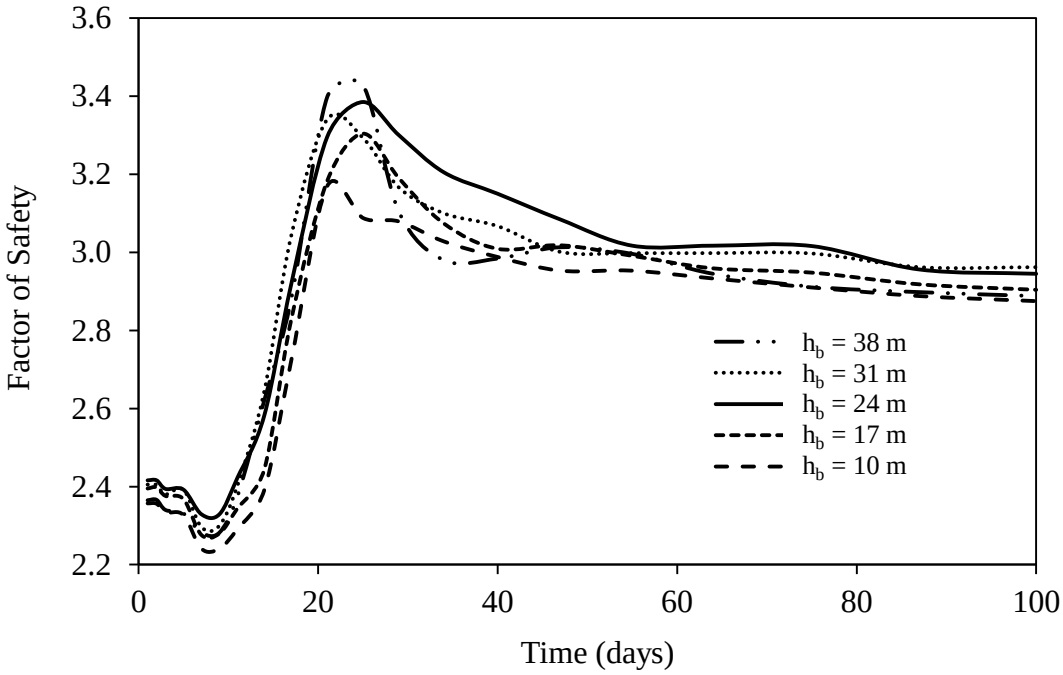


Figure 4-15: Variation of safety factor of upstream slope with respect to time for different upstream berm heights in rapid fill condition

As it can be seen in Figure 4-15, for all cases, safety factor of upstream slope increases rapidly during the first 20 days. After safety factor reaches to a maximum value, it decreases until t=40 days and continues with a constant value until t=100 days. This is because while rapid fill occurs, counter-balancing effect of reservoir water against upstream slope failure is formed. In this period, pore water pressures which trigger upstream slope failure begin to be formed. When t=20 days, pore water pressure begins to increase. Therefore, the factor of safety start to decrease. As soon as pore water pressures reach to the maximum level, the safety factor begins to remain at constant level. Time-dependent safety factors are observed to be satisfactory.

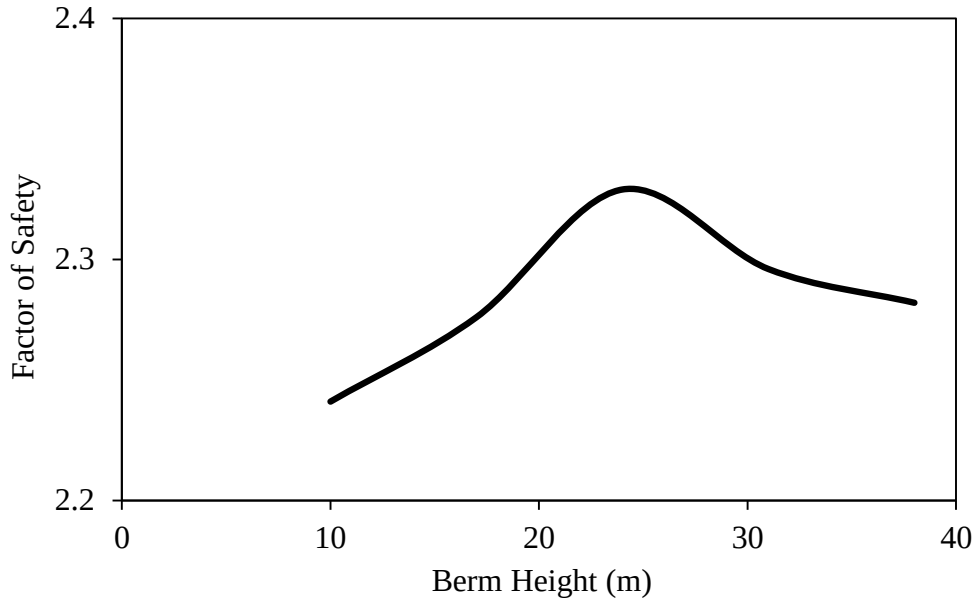


Figure 4-16: Variation of safety factor of upstream slope with respect to upstream berm height in rapid fill condition

In rapid fill condition, increasing the berm height which was constructed at the upstream face, provides higher safety factors of upstream slope of the dam until the ratio of the berm height to the dam height is 0.55. However, when this ratio is greater than this value, lower safety factors are observed in the upstream slope in rapid fill condition. In Figure 4-17, the cross-section of Hancağız Dam is given and the safety factor of the upstream slope in rapid fill condition is shown. Water level increases to 16 m from 2 m and safety factor becomes 2.27 at critical slip surface when t=7 days. In Table 4-15, the variation of the embankment volume and safety factors of each different berm height cases are provided. To show the difference in safety factors four different time steps are considered. In this table, the safety factors of the original case of Hancağız Dam, i.e. having berm height of 17 m at upstream, are indicated with bold numbers. At each increase in berm height, both of the volume of embankment per unit width and safety factor values increases together. But after a critical point, safety factor begins to decrease with increasing berm height and this critical point can be seen in Figure 4-16. Therefore, the berm height to dam height ratio is recommended to be smaller than 0.55.

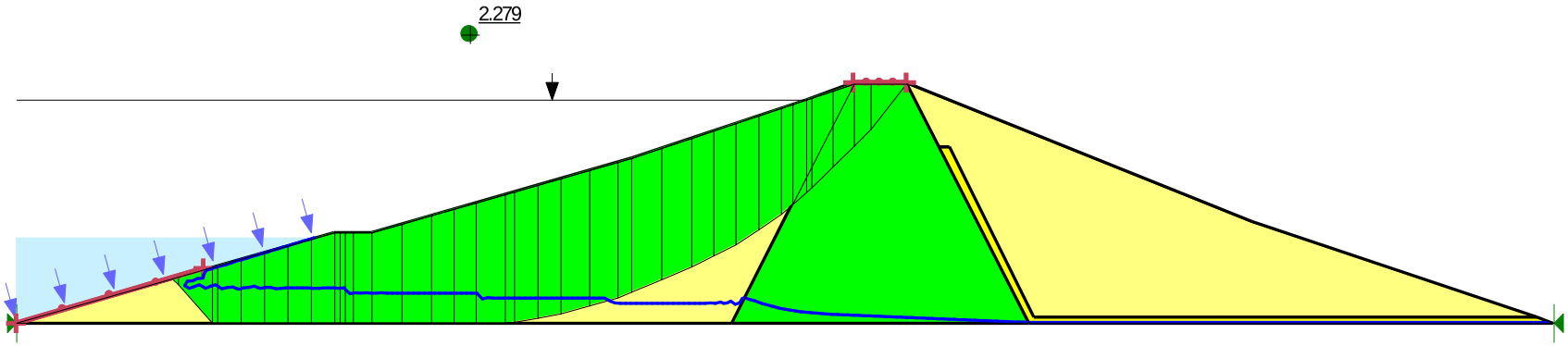


Figure 4-17: Safety factor of upstream slope in rapid fill condition and critical slip surface when t=7 days

Table 4-15: Variation of safety factor of upstream slope and embankment volume for different upstream berm heights in rapid fill condition

Time (days)	**Safety Factor for h_b=17 m**	Safety Factor for h_b=10 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=24 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=31 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=38 m	Difference of Safety Factor	Difference of Volume
1	**2.40**	2.36	-1.6%	-0.7%	2.42	0.9%	0.8%	2.41	0.4%	1.6%	2.37	-1.3%	2.3%
11	**2.34**	2.29	-2.3%		2.42	3.3%		2.40	2.5%		2.37	1.3%	
21	**3.18**	3.17	-0.4%		3.30	3.6%		3.34	5.0%		3.40	6.8%	
40	**3.01**	2.99	-0.7%		3.15	4.7%		3.07	1.9%		2.98	-0.8%	

The effect of the upstream berm number in rapid fill condition is also investigated. The stress based slope stability analysis yielded safety factors as shown in Figure 4-18. As it is seen from this figure, it is obvious that in rapid fill condition, increasing the number of the berm at the upstream face of the dam, provides higher safety factors for the upstream slope of the dam.

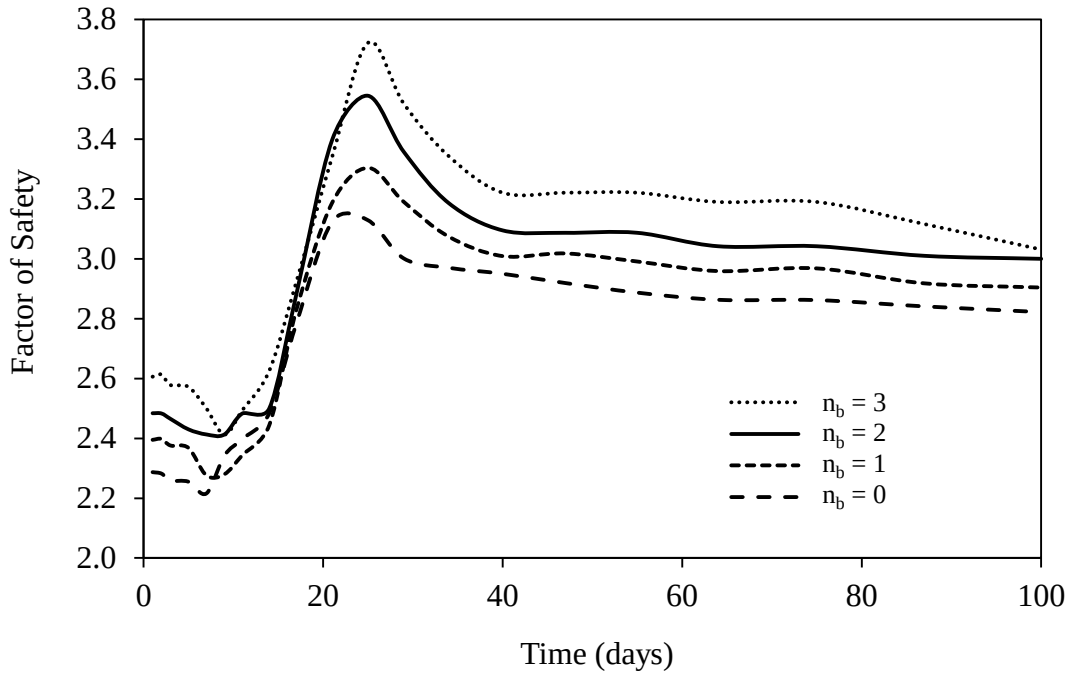


Figure 4-18: Variation of safety factor of upstream slope with respect to time for different upstream berm numbers in rapid fill condition

In Table 4-16, the variation of embankment volume per unit width and safety factors of each different berm number cases are provided. To show the difference in safety factors four different time steps are considered. In this table, the safety factors of the original case of Hancağız Dam, i.e. having one berm at the upstream, are indicated with bold numbers. At each increase in berm number, both of the volume of embankment and safety factor values increases together. According to the table, having two berms is seen to be more beneficial because it results 2.2% increase in the embankment volume. Besides it provides 4.8% increase in the safety factor values.

Table 4-16: Variation of safety factor of upstream slope and embankment volume for different upstream berm numbers in rapid fill condition

Time (days)	**Safety Factor for n_b=1**	Safety Factor for n_b=0	Difference of Safety Factor	Difference of Volume	Safety Factor for n_b=2	Difference of Safety Factor	Difference of Volume	Safety Factor for n_b=3	Difference of Safety Factor	Difference of Volume
1	**2.40**	2.29	-4.7%	-1.1%	2.48	3.7%	2.2%	2.61	8.8%	5.6%
11	**2.34**	2.40	2.3%		2.48	5.9%		2.49	6.4%	
21	**3.19**	3.12	-2.0%		3.40	6.6%		3.34	4.8%	
40	**3.01**	2.95	-2.0%		3.10	2.9%		3.22	7.0%	

The effect of the width of the upstream berm is investigated in rapid fill condition. Figure 4-19 shows the factor of safety values obtained. According to this figure, it is understood that in rapid fill condition, increasing the width of the berm at the upstream side provides higher safety factors of the upstream slope of the dam.

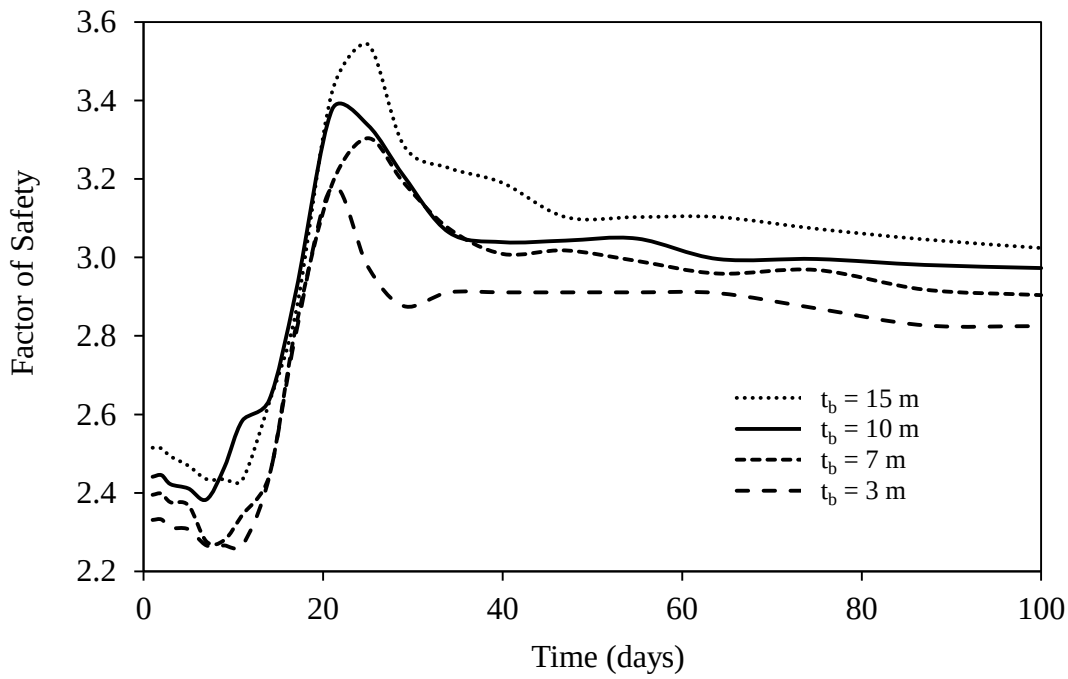


Figure 4-19: Variation of safety factor of upstream slope with respect to time for different upstream berm widths in rapid fill condition

In Table 4-17, the variation of embankment volume per unit width and safety factors of each different berm width cases are provided. To show the difference in safety factors four different time steps are considered. In this table, the safety factors of the original case of Hancağız Dam, i.e. having berm width of 7 m at the upstream, are indicated with bold numbers. At each increase in berm width, both of the embankment volume and safety factor values increases together. Results showed that, it is better to have a width of 10 m, because it provides 4.8% increase in safety factor values; however it causes only 0.8% increase in the embankment volume.

Table 4-17: Variation of safety factor of upstream slope and embankment volume for different upstream berm widths in rapid fill condition

Time (days)	**Safety Factor for t_b=7 m**	Safety Factor for t_b=3 m	Difference of Safety Factor	Difference of Volume	Safety Factor for t_b=10 m	Difference of Safety Factor	Difference of Volume	Safety Factor for t_b=15 m	Difference of Safety Factor	Difference of Volume
1	**2.40**	2.33	-2.7%	-1.1%	2.44	1.9%	0.8%	2.52	5.0%	2.1%
11	**2.34**	2.27	-3.4%		2.58	10.2%		2.43	3.8%	
21	**3.19**	3.18	-0.3%		3.38	6.0%		3.42	7.4%	
40	**3.01**	2.91	-3.4%		3.04	1.0%		3.19	6.0%	

In this study, the safety factors of the downstream slope are also calculated with respect to the variation of the height of the upstream berm and presented in Figure 4-20. Time-dependent safety factors are observed to be satisfactory. It is clear that in rapid fill condition, increasing the height of the berm at the upstream slope of the dam, does not affect safety factors of the downstream slope. This is because, the effects of upstream conditions on pore water pressures of downstream slope is negligible.

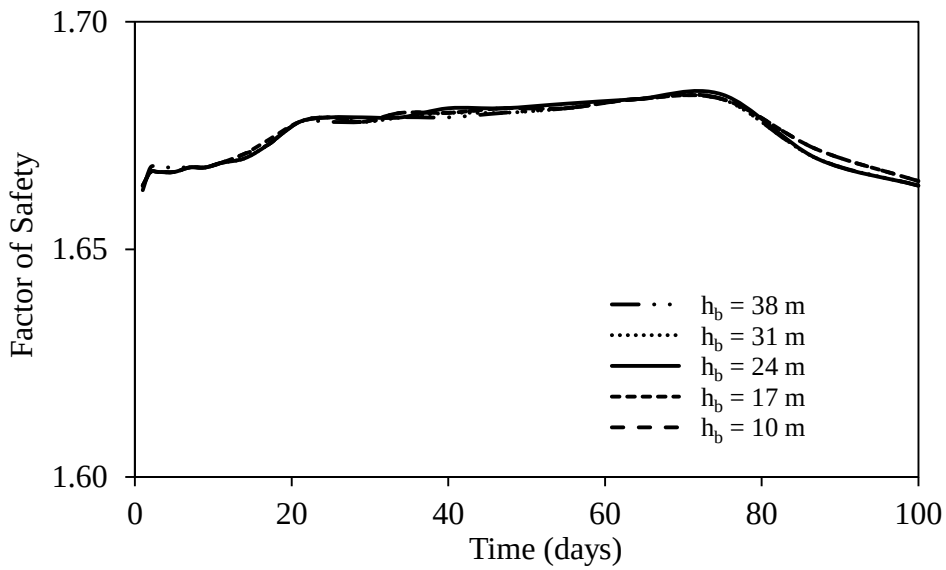


Figure 4-20: Variation of safety factor of downstream slope with respect to time for different upstream berm heights in rapid fill condition

In Figure 4-21, the cross-section of Hancağız Dam is given and the safety factor of downstream slope in rapid fill condition is shown. Water level increases to 16 m from 2 m and safety factor becomes 1.66 at the critical slip surface when t=7 days. In Table 4-18, the variation of embankment volume and safety factors of each different berm height cases are provided. To show the difference in safety factors four different time steps are considered. In this table, the safety factors of the original case of Hancağız Dam, i.e. having berm height of 17 m at upstream, are indicated with bold numbers. At each increase in berm height, only the embankment volume increases, safety factor values do not change.

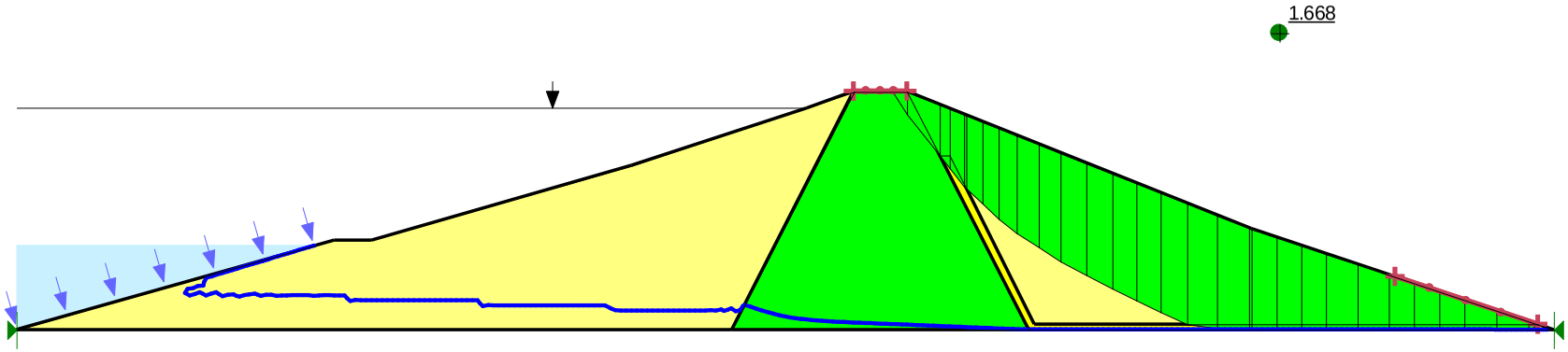


Figure 4-21: Safety factor of downstream slope in rapid fill condition and critical slip surface when t=7 days

Table 4-18: Variation of safety factor of downstream slope and embankment volume for different upstream berm heights in rapid fill condition

Time (days)	**Safety Factor for h_b=17 m**	Safety Factor for h_b=10 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=24 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=31 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=38 m	Difference of Safety Factor	Difference of Volume
1	**1.66**	1.66	0.0%	-0.7%	1.66	0.0%	0.8%	1.66	0.0%	1.6%	1.66	-0.1%	2.3%
11	**1.67**	1.67	0.0%		1.67	0.0%		1.67	0.0%		1.67	0.0%	
21	**1.68**	1.68	0.0%		1.68	0.0%		1.68	0.0%		1.68	0.0%	
40	**1.68**	1.68	0.0%		1.68	0.1%		1.68	0.0%		1.68	-0.1%	

In the study, the number of upstream berms are altered in rapid fill condition. Then safety factors are obtained for the downstream slope. The values are presented in Figure 4-22. As it can be explicitly seen in Figure 4-22, there is no difference between the cases. In rapid fill condition, increasing the number of the berm at the upstream slope of the dam, does not affect safety factors of the downstream slope. In all cases factor of safety does not change significantly. This is because, effects of upstream conditions on pore water pressures of downstream slope are negligible.

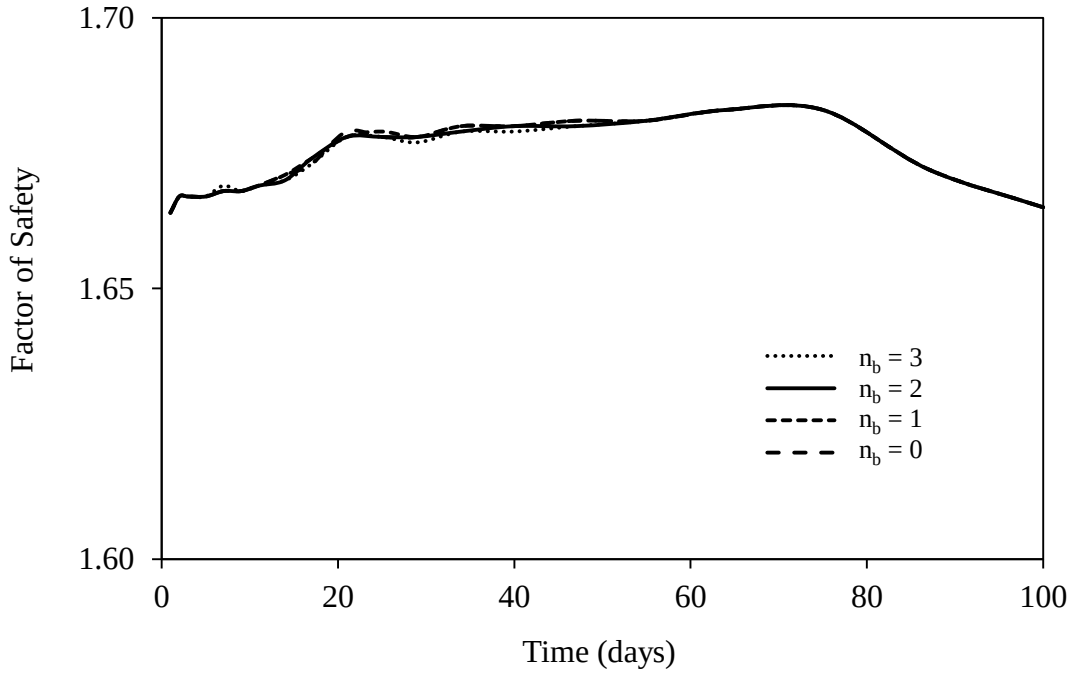


Figure 4-22: Variation of safety factor of downstream slope with respect to time for different upstream berm numbers in rapid fill condition

In Table 4-19, the variation of embankment volume per unit width and safety factors of each different berm number cases are provided. To show the difference in safety factors four different time steps are considered. In this table, the safety factors of the original case of Hancağız Dam, i.e. having one berm at the upstream, are indicated with bold numbers. At each increase in berm number, only the embankment volume increases, safety factor values remain the same.

Table 4-19: Variation of safety factor of downstream slope and embankment volume for different upstream berm numbers in rapid fill condition

Time (days)	**Safety Factor for n_b=1**	Safety Factor for n_b=0	Difference of Safety Factor	Difference of Volume	Safety Factor for n_b=2	Difference of Safety Factor	Difference of Volume	Safety Factor for n_b=3	Difference of Safety Factor	Difference of Volume
1	**1.66**	1.66	0.0%	-1.1%	1.66	0.0%	2.2%	1.66	0.0%	5.6%
11	**1.67**	1.67	0.0%		1.67	0.0%		1.67	0.0%	
21	**1.68**	1.68	0.1%		1.68	0.0%		1.68	0.0%	
40	**1.68**	1.68	0.0%		1.68	0.0%		1.68	-0.1%	

The effect of the upstream berm width on safety factor of the downstream slope is analyzed for rapid fill condition. The safety factors for the cases of different berm widths are shown in Figure 4-23. According to Figure 4-23, the factor of safety variation for different cases are almost the same. Therefore, in rapid fill condition, increasing the width of the berm at the upstream slope of the dam does not affect safety factors of the downstream slope. This is because, the effects of upstream conditions on pore water pressures of downstream slope is slight.

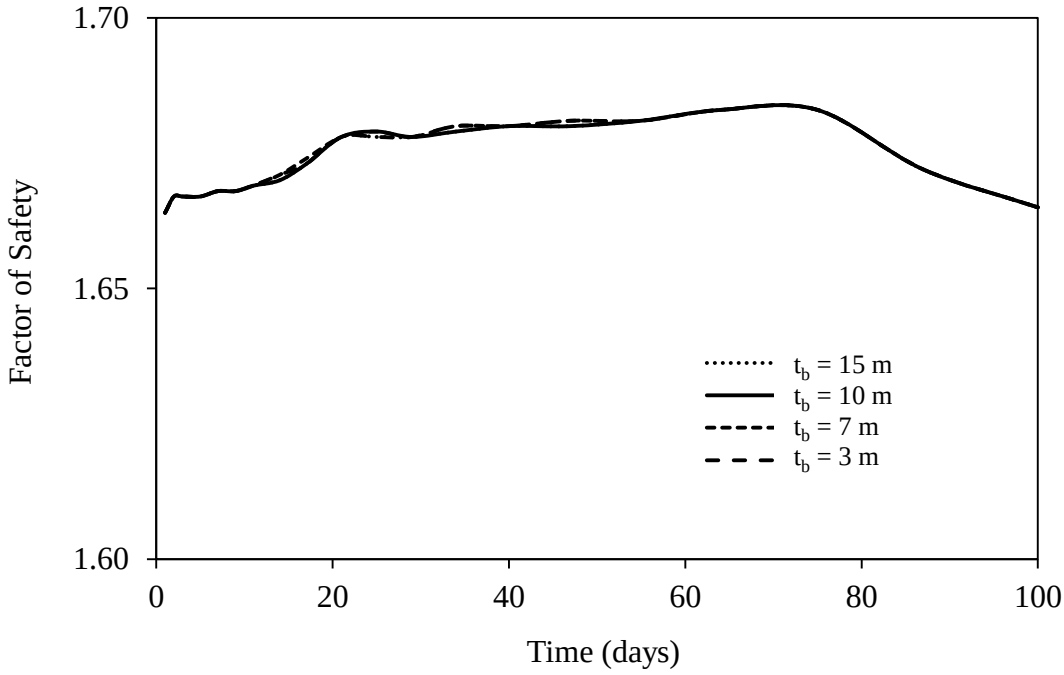


Figure 4-23: Variation of safety factor of downstream slope with respect to time for different upstream berm widths in rapid fill condition

In Table 4-20, the variation of embankment volume per unit width and safety factors of each different berm cases are provided. To show the difference in safety factors four different time steps are considered. In this table, the safety factors of the original case of Hancağız Dam, i.e. having berm width of 7 m at upstream, are indicated with bold numbers. At each increase in berm width, only the embankment volume increases, safety factor values remain constant.

Table 4-20: Variation of safety factor of downstream slope and embankment volume for different upstream berm widths in rapid fill condition

Time (days)	**Safety Factor for t_b=7 m**	Safety Factor for t_b=3 m	Difference of Safety Factor	Difference of Volume	Safety Factor for t_b=10 m	Difference of Safety Factor	Difference of Volume	Safety Factor for t_b=15 m	Difference of Safety Factor	Difference of Volume
1	**1.66**	1.66	0.0%	-1.1%	1.66	0.0%	0.8%	1.66	0.0%	2.1%
11	**1.67**	1.67	0.0%		1.67	0.0%		1.67	0.0%	
21	**1.68**	1.68	0.0%		1.68	0.0%		1.68	0.0%	
40	**1.68**	1.68	0.0%		1.68	0.0%		1.68	0.0%	

The effect of the height of the berm on safety factor of the upstream slope is investigated for steady-state seepage condition when there is a berm at the upstream face. To this end, both limit equilibrium and stress-based finite element methods are used. Among the limit equilibrium methods Spencer technique is considered. When the reservoir water level stays at the maximum level for a long time, pore water pressures develop through the dam body. High pore water pressures near the upstream slope are counterbalanced by water acting on the upstream face of dam. So there is no critical situation for the upstream slope in steady-state seepage condition. Since there is no water acting on the downstream face of the dam, high pore water pressures near the downstream slope cause critical situation for the downstream slope.

For cases of different berm heights, factor of safety values are shown in Figure 4-24 using the finite element method (FEM). In FEM solution, increasing the berm height which was constructed at the upstream face, provides higher safety factors for the upstream slope of the dam until the ratio of berm height to dam height is 0.66. However, after the ratio of berm height to dam height exceeds 0.66, increasing the berm height which was constructed at the upstream face causes lower safety factors for the upstream slope in steady-state seepage condition.

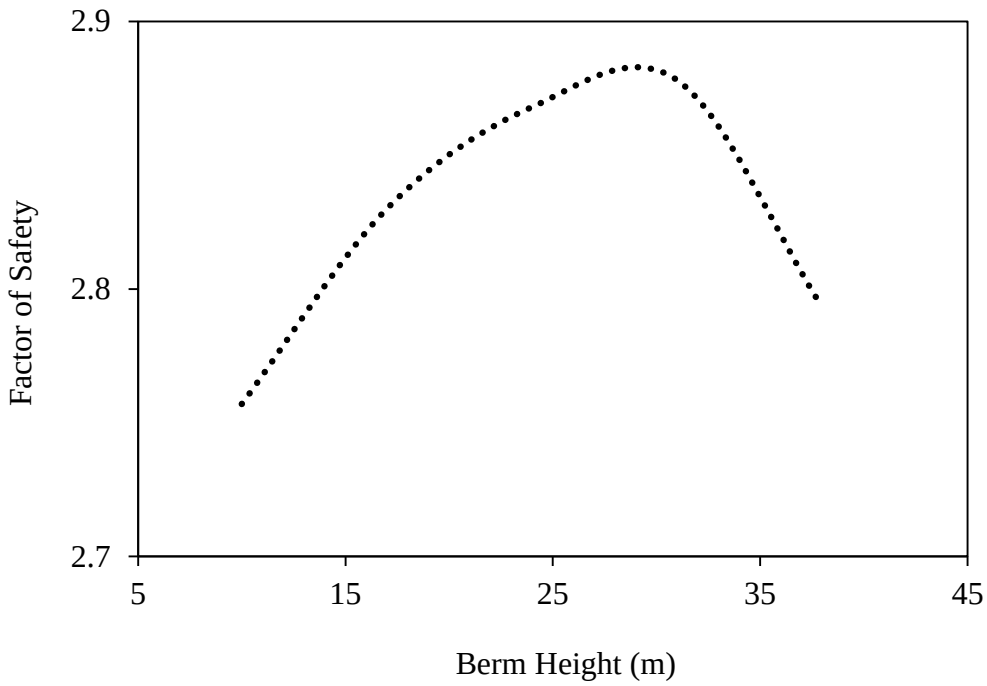


Figure 4-24: Variation of safety factor of upstream slope with respect to upstream berm height in steady-state seepage condition

In Figure 4-25, the cross-section of Hancağız Dam is given and safety factor of upstream slope in steady-state seepage condition is shown. Water level remains constant at 42 m during seepage. Safety factor becomes 2.83 at the critical slip surface for original case of Hancağız Dam. Safety factors which were obtained for different berm height cases are greater than the minimum required values (see Table 2-2). In Table 4-21, the variation of embankment volume per unit width and safety factors of each different berm height cases are provided by using finite element method. The safety factors of the original case of Hancağız Dam, i.e. having a berm height of 17 m at the upstream, are indicated with bold numbers. At each increase in berm height, both of the embankment volume and safety factor values increase together. But after a critical point, safety factor begins to decrease with increasing berm height. This critical point can be seen in Figure 4-24. It makes sense to choose the value of the berm height, such that the ratio of berm height to dam height becomes 0.55.

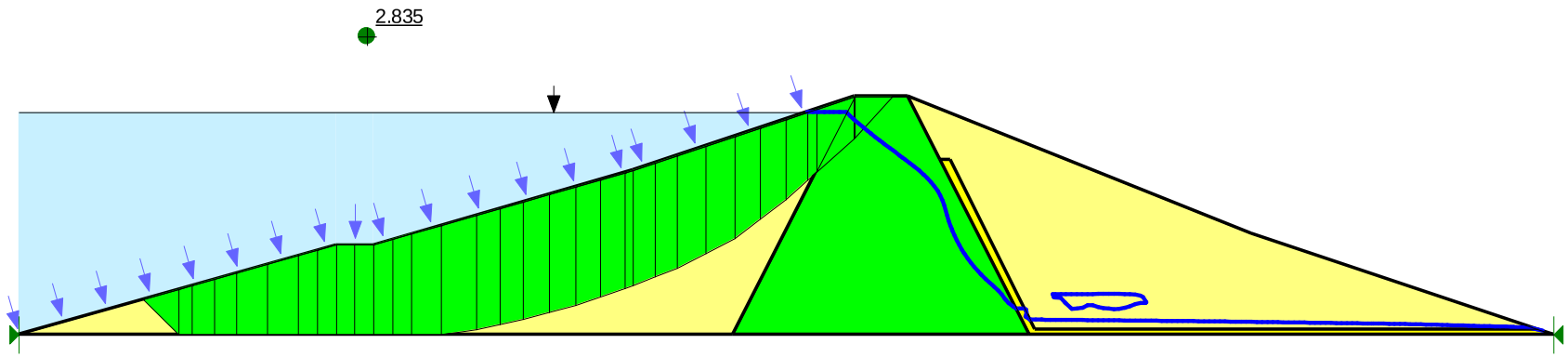


Figure 4-25: Safety factor of upstream slope in steady-state seepage condition and critical slip surface

Table 4-21: Variation of safety factor of upstream slope and embankment volume for different upstream berm heights in steady-state seepage condition

Safety Factor for h_b=17 m	Safety Factor for h_b=10 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=24 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=31 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=38 m	Difference of Safety Factor	Difference of Volume
2.83	2.76	-2.6%	-0.7%	2.87	1.3%	0.8%	2.88	1.7%	1.6%	2.79	-1.3%	2.3%

The number of the upstream berm is varied to investigate the effect of berm number on safety factor in the study. The factor of safety values for the upstream slope are shown in Figure 4-26. Increasing the number of the berm at the upstream face of the dam, provides higher safety factors for the upstream slope of the dam in steady-state seepage condition.

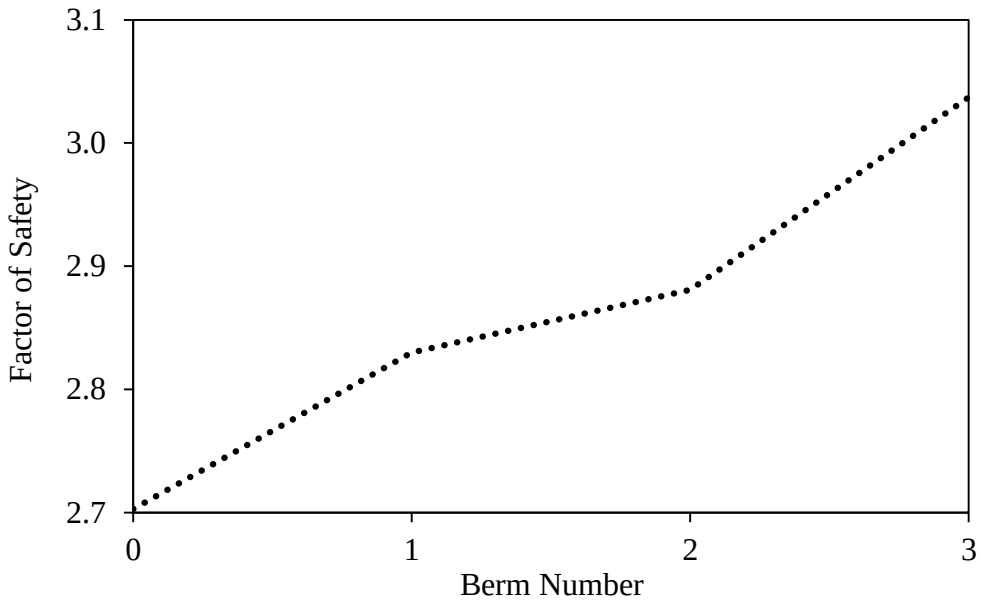


Figure 4-26: Variation of safety factor of upstream slope with respect to upstream berm number in steady-state seepage condition

In Table 4-22, the variation of embankment volume per unit width and safety factors of each different berm number cases are provided. The safety factors of the original case of Hancağız Dam, i.e. having one berm at upstream, are indicated with bold numbers. At each increase in berm number, both of the embankment volume and safety factor values increase together. It seems reasonable to have one berm than no berm because when dam has one berm, it provides 4.7% increase in the safety factor whereas 1.1% increase in the embankment volume.

Table 4-22: Variation of safety factor of upstream slope and embankment volume for different upstream berm numbers in steady-state seepage condition

Safety Factor for n_b=1	Safety Factor for n_b=0	Difference of Safety Factor	Difference of Volume	Safety Factor for n_b=2	Difference of Safety Factor	Difference of Volume	Safety Factor for n_b=3	Difference of Safety Factor	Difference of Volume
2.83	2.70	-4.7%	-1.1%	2.88	1.8%	2.2%	3.04	7.3%	5.6%

The effect of the width of the berm on safety factor of the upstream slope is analyzed for steady-state seepage condition when berm is at the upstream face of the dam. For cases of different berm width, factor of safety values are shown in Figure 4-27. Increasing the width of the berm at the upstream face of the dam, provides higher safety factors of the upstream slope of the dam.

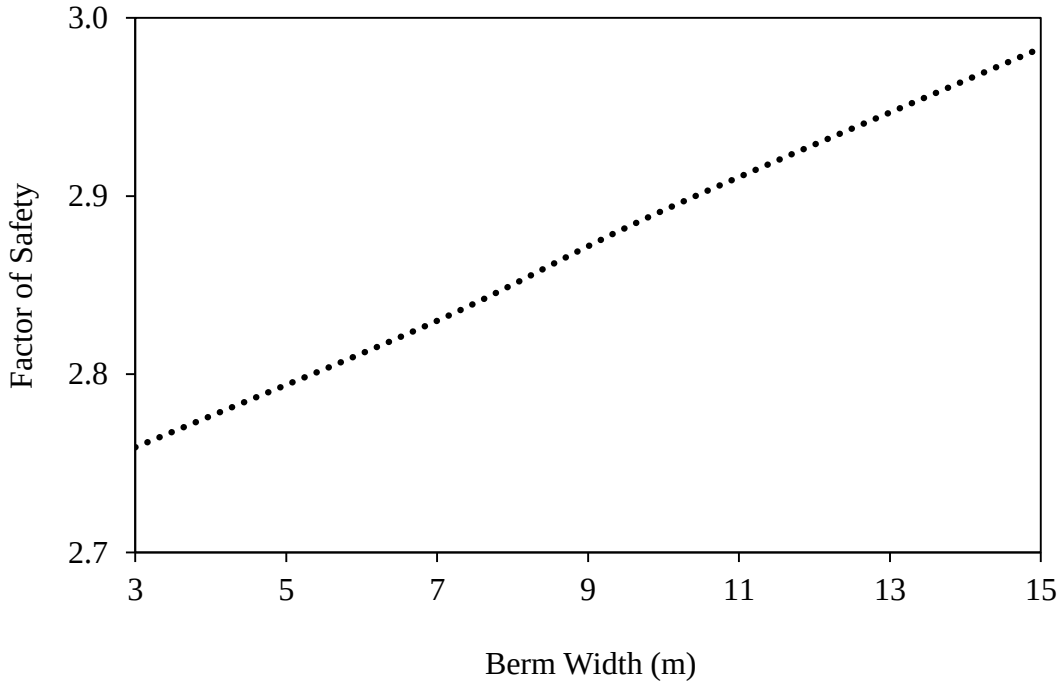


Figure 4-27: Variation of safety factor of upstream slope with respect to upstream berm width in steady-state seepage condition

In Table 4-23, the variation of embankment volume per unit width and safety factors of each different berm width cases are provided. The safety factor of the original case of Hancağız Dam, i.e. having berm width of 7 m at upstream, are indicated with bold numbers. At each increase in berm width, both of the embankment volume and safety factor values increase together. It seems beneficial to choose 10 m for the berm width since the increase in safety factor is three times the increase in embankment volume when it is compared with the original case.

Table 4-23: Variation of safety factor of upstream slope and embankment volume for different upstream berm widths in steady-state seepage condition

Safety Factor for t_b=7 m	Safety Factor for t_b=3 m	Difference of Safety Factor	Difference of Volume	Safety Factor for t_b=10 m	Difference of Safety Factor	Difference of Volume	Safety Factor for t_b=15 m	Difference of Safety Factor	Difference of Volume
2.83	2.76	-2.6%	-1.1%	2.89	2.2%	0.8%	2.98	5.4%	2.1%

The effect of the height of the berm on safety factor of the downstream slope is analyzed for steady-state seepage condition when the berm is at the upstream face of the dam. For different berm height cases, factor of safety values, are shown in Figure 4-28. In steady-state seepage condition, increasing the height of the berm at the upstream slope of the dam does not affect safety factors of the downstream slope.

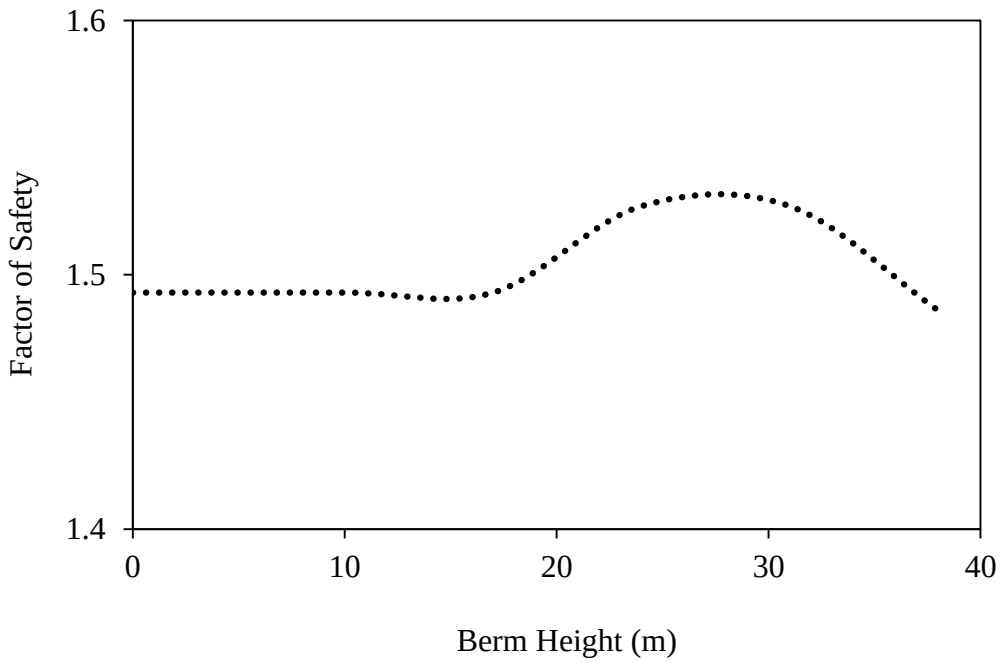


Figure 4-28: Variation of safety factor of downstream slope with respect to upstream berm height in steady-state seepage condition

In Figure 4-29, the cross-section of Hancağız Dam is given and safety factor of the downstream slope in steady-state seepage condition is shown. Water level remains constant at 42 m during seepage and safety factor becomes 1.49 at the critical slip surface. In Table 4-24, the variation of embankment volume per unit width and safety factors of each different berm height cases are provided. The safety factors of the original case of Hancağız Dam, i.e. having berm height of 17 m at the upstream, are indicated with bold numbers. In FEM-based slope stability analysis, an increase by 2.3% in the safety factor is seen when berm height values are 24 m and 31 m.

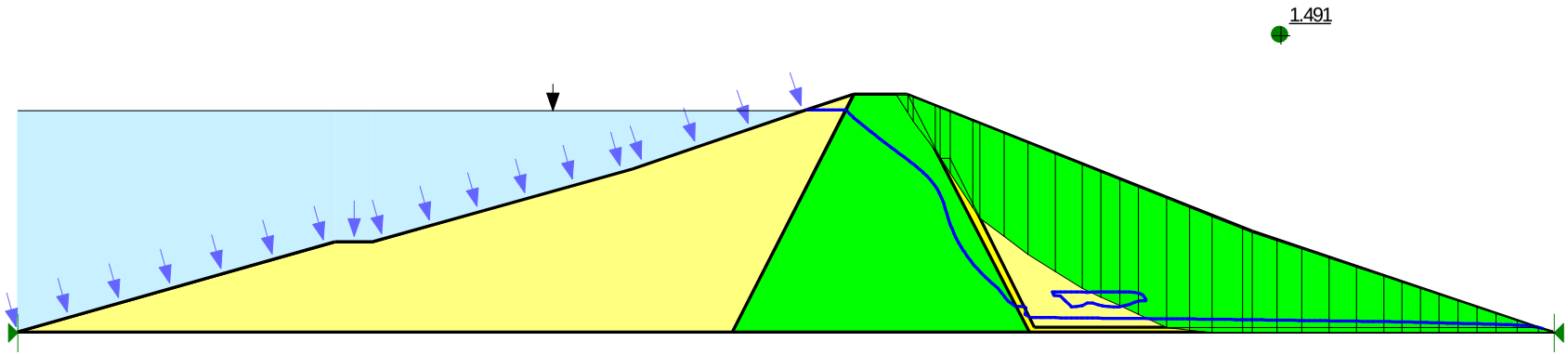


Figure 4-29: Safety factor of downstream slope in steady-state seepage condition and critical slip surface

Table 4-24: Variation of safety factor of downstream slope and embankment volume for different upstream berm heights in steady-state seepage condition

Safety Factor for h_b=17 m	Safety Factor for h_b=10 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=24 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=31 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=38 m	Difference of Safety Factor	Difference of Volume
1.49	1.49	0.0%	-0.7%	1.53	2.3%	0.8%	1.53	2.3%	1.6%	1.49	-0.5%	2.3%

The effect of the number of the upstream berms on safety factor of the downstream slope is calculated for steady-state seepage condition. In the steady-state seepage condition, increasing the number of the berm at the upstream slope of the dam does not affect safety factor i.e. 1.49 for the downstream slope.

In Table 4-25, the variation of embankment volume per unit width and safety factors of each different berm number cases are provided. The safety factors of the original case of Hancağız Dam, i.e. having one berm at the upstream, are indicated with bold numbers. According to the table, safety factors remain same with the increase of the embankment volume.

Table 4-25: Variation of safety factor of downstream slope and embankment volume for different upstream berm numbers in steady-state seepage condition

Safety Factor for n_b=1	Safety Factor for n_b=0	Difference of Safety Factor	Difference of Volume	Safety Factor for n_b=2	Difference of Safety Factor	Difference of Volume	Safety Factor for n_b=3	Difference of Safety Factor	Difference of Volume
1.49	1.49	0.0%	-1.1%	1.49	0.0%	2.2%	1.49	0.1%	5.6%

The width of the upstream berm is varied to investigate effect of berm width on dam safety. Increasing the width of the berm at the upstream slope of the dam in steady-state seepage condition, does not affect safety factor i.e. 1.49 for the downstream slope when FEM is used.

In Table 4-26, the variation of embankment volume per unit width and safety factors of each different berm width cases are provided. Safety factor values are based on FEM. The safety factors of the original case of Hancağız Dam, i.e. having berm width of 7 m at upstream, are indicated with bold numbers. Safety factors do not change significantly with the increasing embankment volume.

Table 4-26: Variation of safety factor of downstream slope and embankment volume for different upstream berm widths in steady-state seepage condition

Safety Factor for t_b=7 m	Safety Factor for t_b=3 m	Difference of Safety Factor	Difference of Volume	Safety Factor for t_b=10 m	Difference of Safety Factor	Difference of Volume	Safety Factor for t_b=15 m	Difference of Safety Factor	Difference of Volume
1.49	1.49	0.0%	-1.1%	1.49	0.0%	0.8%	1.49	0.0%	2.1%

The effect of the height of the berm on safety factor of the upstream slope is analyzed for rapid drawdown condition when the berm is at the downstream face of the dam. By using Sigma/W Stress analysis type, cases of different berm heights are examined. Factor of safety values during 100 days are given in Figure 4-30. As it is shown in Figure 4-30, lines are overlapping. It can be said that in rapid drawdown condition, increasing height of the berm at the downstream slope of the dam does not affect safety factors of upstream slope. Time-dependent safety factors are greater than the minimum required values (see Table 2-1).

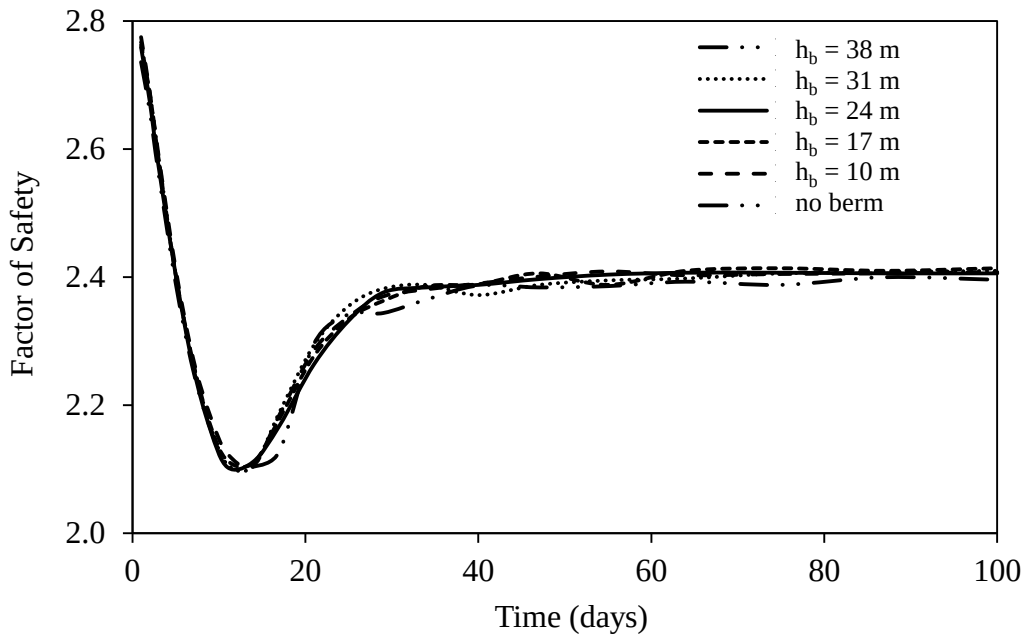


Figure 4-30: Variation of safety factor of upstream slope with respect to time for different downstream berm heights in rapid drawdown condition

In Table 4-27, the variation of embankment volume per unit width and safety factors of each different berm height cases are provided. To show the difference in safety factors four different time steps are considered. In this table, the safety factors of the reference case of Hancağız Dam, i.e. having no berm at the downstream, are indicated with bold numbers. At each increase in berm height, only the embankment volume increases, whereas the safety factor values do not change remarkably.

Table 4-27: Variation of safety factor of upstream slope and embankment volume for different downstream berm heights in rapid drawdown condition

Time (days)	**Safety Factor for No Berm**	Safety Factor for h_b=10 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=17 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=24 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=31 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=38 m	Difference of Safety Factor	Difference of Volume
1	**2.74**	2.78	1.4%	1.0%	2.76	1.0%	1.7%	2.76	0.8%	2.4%	2.77	1.1%	4.1%	2.75	0.5%	4.9%
11	**2.11**	2.12	0.9%		2.11	0.3%		2.10	-0.1%		2.11	0.0%		2.11	0.0%	
21	**2.30**	2.29	-0.4%		2.28	-0.8%		2.26	-1.4%		2.29	-0.1%		2.27	-1.1%	
40	**2.39**	2.39	0.1%		2.39	0.1%		2.39	0.0%		2.37	-0.6%		2.40	0.3%	

The effect of the number of the downstream berms on safety factor of the upstream slope is investigated in rapid drawdown condition. By utilizing the Sigma/W Stress, safety factors for cases of different berm numbers are given in Figure 4-31. There are no remarkable variation in lines of different cases. For this reason, it can be said that in rapid drawdown condition, increasing the number of the berm at the downstream slope of the dam, does not affect safety factors of the upstream slope.

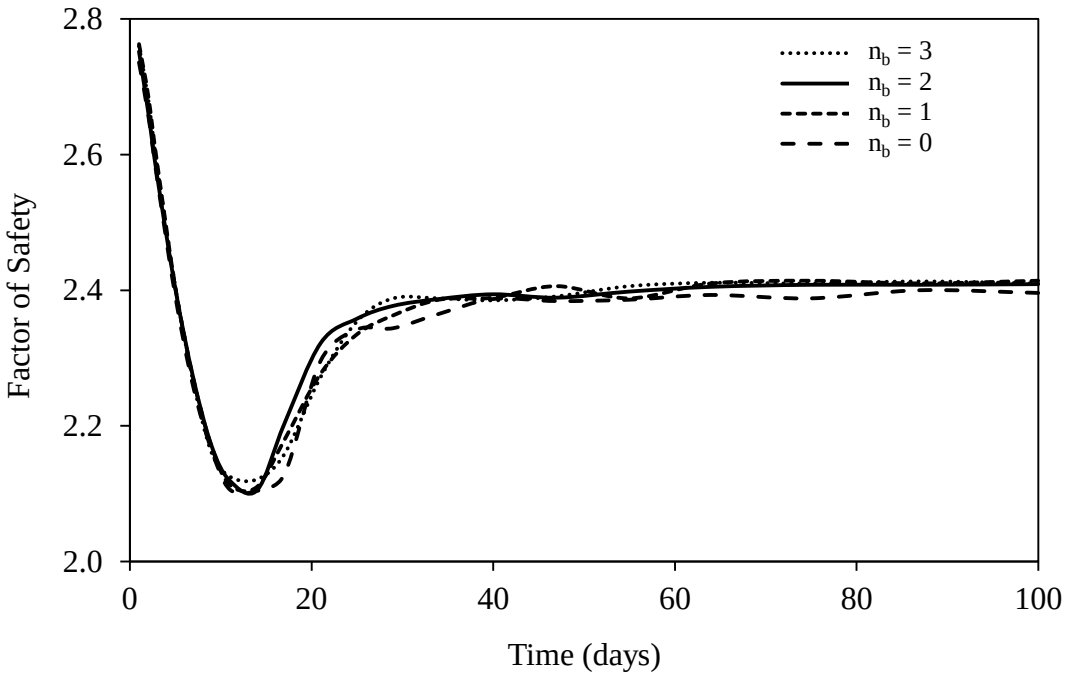


Figure 4-31: Variation of safety factor of upstream slope with respect to time for different downstream berm numbers in rapid drawdown condition

In Table 4-28, the variation of embankment volume per unit width and safety factors of each different berm number cases are provided. To show the difference in safety factors four different time steps are considered. The safety factors of the reference case of Hancağız Dam, i.e. having no berm at the downstream, are indicated with bold numbers. At each increase in berm number, only the embankment volume increases, whereas safety factor values do not change significantly.

Table 4-28: Variation of safety factor of upstream slope and embankment volume for different downstream berm numbers in rapid drawdown condition

Time (days)	**Safety Factor for n_b=0**	Safety Factor for n_b=1	Difference of Safety Factor	Difference of Volume	Safety Factor for n_b=2	Difference of Safety Factor	Difference of Volume	Safety Factor for n_b=3	Difference of Safety Factor	Difference of Volume
1	**2.74**	2.76	1.0%	1.7%	2.75	0.6%	2.9%	2.76	0.9%	6.0%
11	**2.11**	2.11	0.3%		2.12	0.6%		2.13	0.9%	
21	**2.30**	2.28	-0.8%		2.32	1.1%		2.27	-1.0%	
40	**2.39**	2.39	0.1%		2.39	0.3%		2.39	-0.1%	

The effect of the width of the downstream berm on safety factor of the upstream slope is investigated in rapid drawdown condition. By using analysis type of Sigma/W Stress, factor of safety values during 100 days, are presented in Figure 4-32. There is no considerable variation in lines of different cases in Figure 4-32. Therefore, it can be said that in rapid drawdown condition, increasing the width of the berm at the downstream slope of the dam, does not affect safety factors of the upstream slope.

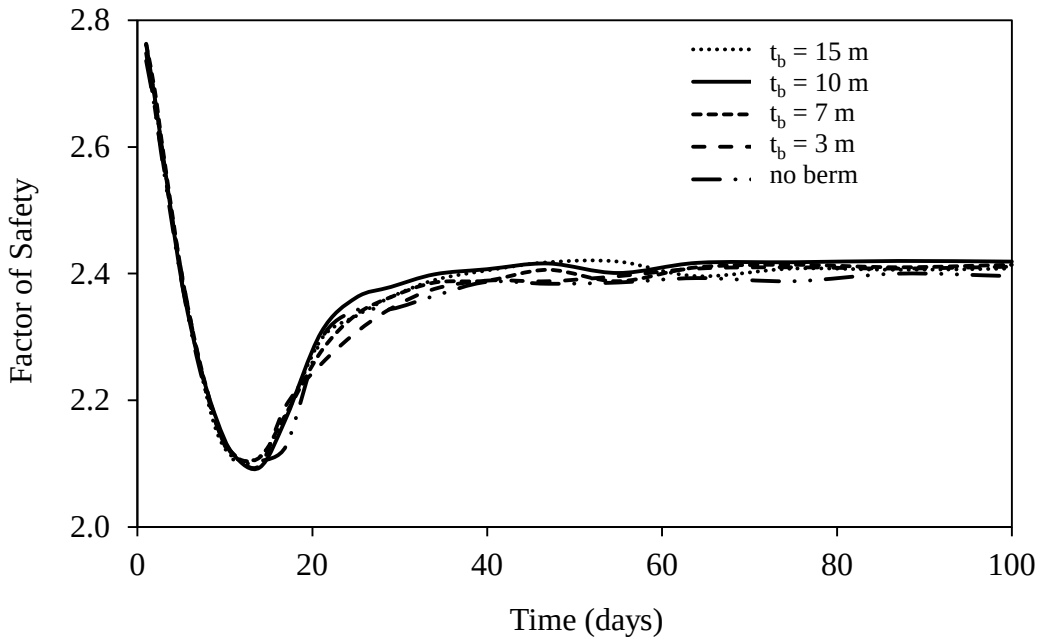


Figure 4-32: Variation of safety factor of upstream slope with respect to time for different downstream berm widths in rapid drawdown condition

In Table 4-29, the variation of embankment volume per unit width and safety factors of each different berm width cases are provided. To show the difference in safety factors four different time steps are considered. In this table, the safety factors of the original case of Hancağız Dam, i.e. having no berm at the downstream, are indicated with bold numbers. At each increase in berm number, only the embankment volume increases, whereas safety factor values do not change significantly.

Table 4-29: Variation of safety factor of upstream slope and embankment volume for different downstream berm widths in rapid drawdown condition

Time (days)	**Safety Factor for No Berm**	Safety Factor for t_b=3 m	Difference of Safety Factor	Difference of Volume	Safety Factor for t_b=7 m	Difference of Safety Factor	Difference of Volume	Safety Factor for t_b=10 m	Difference of Safety Factor	Difference of Volume	Safety Factor for t_b=15 m	Difference of Safety Factor	Difference of Volume
1	**2.74**	2.75	0.4%	0.7%	2.76	1.0%	1.7%	2.76	1.0%	2.5%	2.76	0.9%	3.7%
11	**2.11**	2.12	0.4%		2.11	0.3%		2.11	0.4%		2.11	0.2%	
21	**2.30**	2.26	-1.7%		2.28	-0.8%		2.31	0.5%		2.30	0.0%	
40	**2.39**	2.39	0.1%		2.39	0.1%		2.41	0.8%		2.41	0.8%	

The height of the downstream berm is varied to search the effect of berm height on safety factor of downstream slope. By using Sigma/W Stress, factor of safety values for different berm heights, are shown in Figure 4-33. Also factor of safety values with respect to berm height are given in Figure 4-34. In rapid drawdown condition, increasing the berm height which is constructed at the downstream slope, provides higher safety factors of the downstream slope of the dam until the ratio of berm height to dam height is 0.55. However, after this ratio exceeds 0.55, increasing the berm height which is constructed at the downstream, causes lower safety factors of downstream slope in rapid drawdown condition. Time-dependent safety factors are greater than the minimum required values (see Table 2-1).

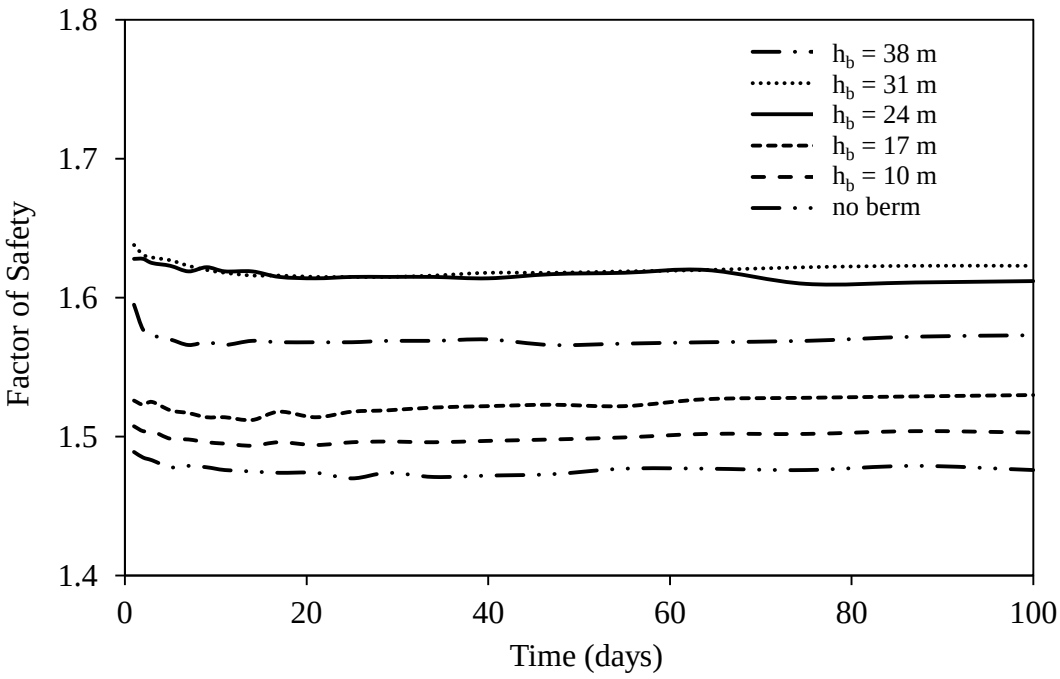


Figure 4-33: Variation of safety factor of downstream slope with respect to time for different downstream berm heights in rapid drawdown condition

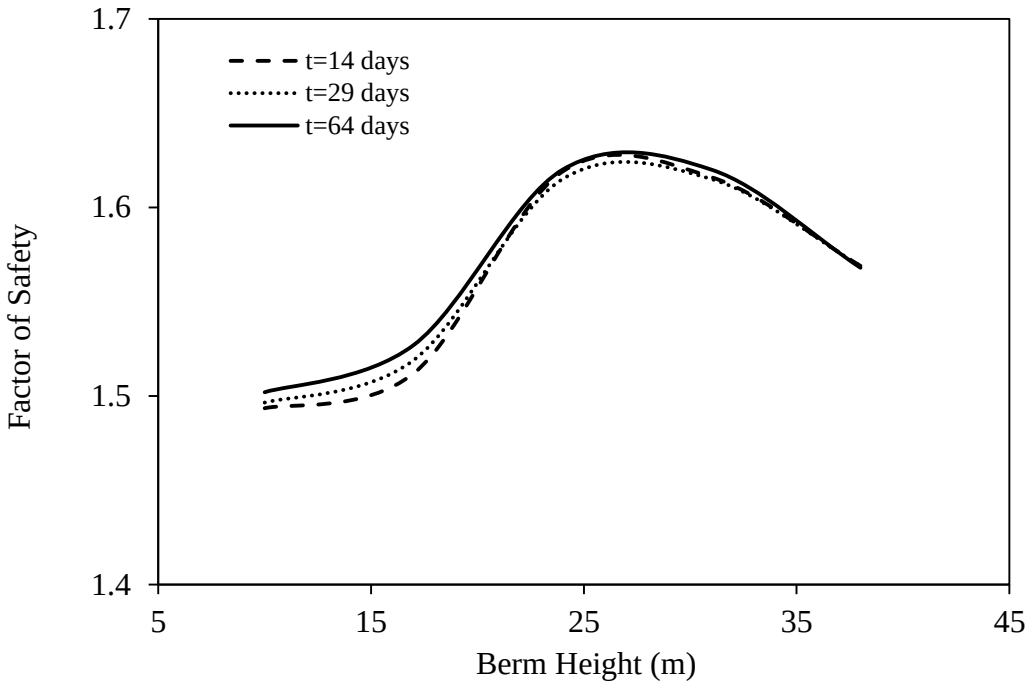


Figure 4-34: Variation of safety factor of downstream slope with respect to downstream berm heights in rapid drawdown condition

In Table 4-30, the variation of embankment volume per unit width and safety factors of each different berm height cases are provided. To show the difference in safety factors four different time steps are considered. Safety factors of the original case of Hancağız Dam, i.e. having no berm at the downstream are indicated with bold numbers. At each increases in berm height, both of the volume of embankment and safety factor values increase together. But after a critical point, safety factor begins to decrease with increasing berm height as shown in Figure 4-36. It makes sense to choose the value of berm height such that the ratio of berm height to dam height becomes 0.55.

Table 4-30: Variation of safety factor of downstream slope and embankment volume for different downstream berm heights in rapid drawdown condition

Time (days)	**Safety Factor for No Berm**	Safety Factor for h_b=10 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=17 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=24 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=31 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=38 m	Difference of Safety Factor	Difference of Volume
1	**1.49**	1.51	1.2%	1.0%	1.53	2.5%	1.7%	1.63	9.3%	2.4%	1.64	10.0%	4.1%	1.60	7.1%	4.9%
11	**1.48**	1.50	1.3%		1.51	2.6%		1.62	9.7%		1.62	9.6%		1.57	6.1%	
21	**1.47**	1.49	1.4%		1.51	2.7%		1.61	9.5%		1.62	9.6%		1.57	6.4%	
40	**1.47**	1.50	1.7%		1.52	3.4%		1.61	9.6%		1.62	9.9%		1.57	6.7%	

The effect of the number of berms on safety factor of downstream slope is analyzed for rapid drawdown condition when the berm is at the downstream face of the dam. Sigma/W Stress is used for cases of different berm numbers. Factor of safety values during 100 days, are shown in Figure 4-35. Time-dependent safety factors are greater than the minimum required values (see Table 2-1). It is obvious that in rapid drawdown condition, increasing the number of berms at the downstream face of the dam, provides higher safety factors for the downstream slope of the dam.

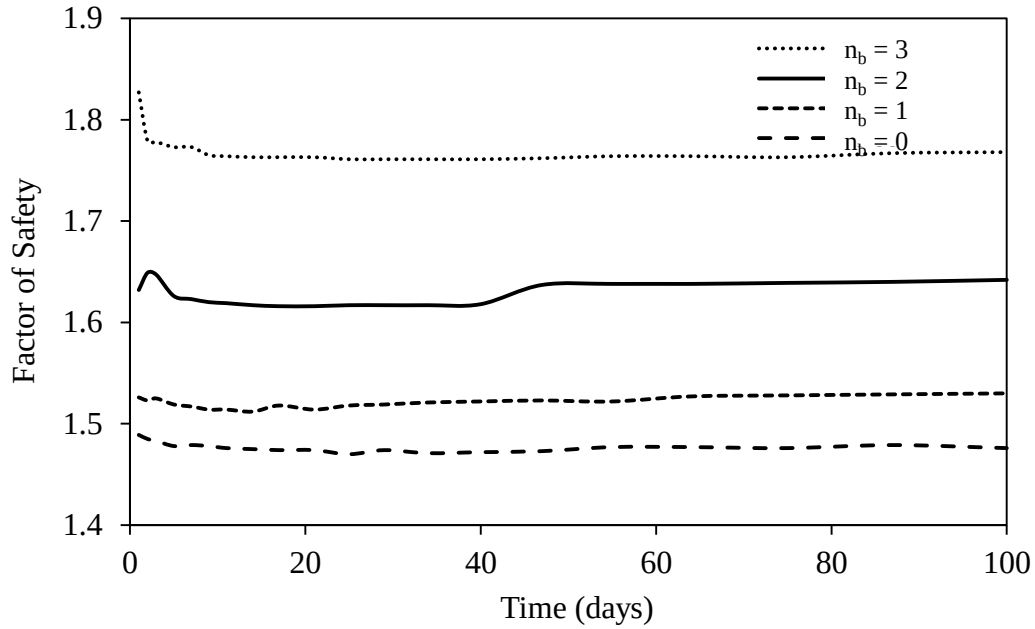


Figure 4-35: Variation of safety factor of downstream slope with respect to time for different downstream berm numbers in rapid drawdown condition

In Table 4-31, the variation of embankment volume per unit width and safety factors of each different berm number cases are provided. To show the difference in safety factors four different time steps are considered. The safety factors of the original case of Hancağız Dam, i.e. having no berm at the downstream, are indicated with bold numbers. At each increase in berm number, both of the volume of embankment and safety factor values increase together. It is better that dam has three berms since the increase in safety factor is three times the increase in embankment volume.

Table 4-31: Variation of safety factor of downstream slope and embankment volume for different downstream berm numbers in rapid drawdown condition

Time (days)	**Safety Factor for n_b=0**	Safety Factor for n_b=1	Difference of Safety Factor	Difference of Volume	Safety Factor for n_b=2	Difference of Safety Factor	Difference of Volume	Safety Factor for n_b=3	Difference of Safety Factor	Difference of Volume
1	**1.49**	1.53	2.5%	1.7%	1.63	9.6%	2.9%	1.83	22.7%	6.0%
11	**1.48**	1.51	2.6%		1.62	9.7%		1.76	19.5%	
21	**1.47**	1.51	2.7%		1.62	9.6%		1.76	19.6%	
40	**1.47**	1.52	3.4%		1.62	9.9%		1.76	19.6%	

The effect of the width of the berm on safety factor of downstream slope is analyzed for rapid drawdown condition when the berm is at the downstream slope of the dam. By using Sigma/W Stress for cases of different berm width, factor of safety values during 100 days, are presented in Figure 4-36. Time-dependent safety factors are greater than the minimum required values (see Table 2-1). It is clear that in rapid drawdown condition, increasing width of the berm at downstream face of the dam, provides higher safety factors for the downstream slope of the dam.

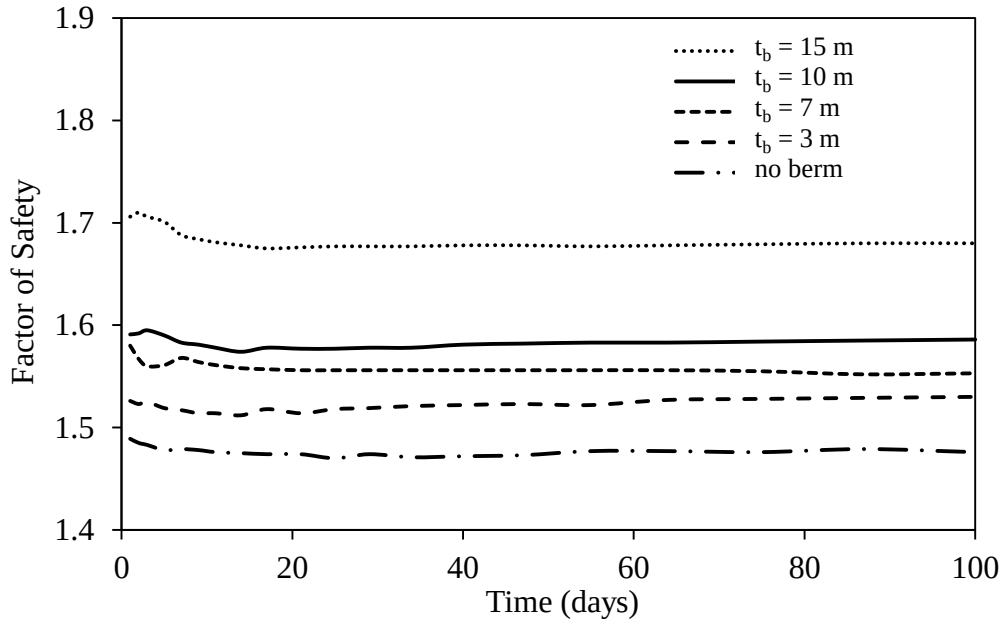


Figure 4-36: Variation of safety factor of downstream slope with respect to time for different downstream berm widths in rapid drawdown condition

In Table 4-32, the variation of embankment volume per unit width and safety factors of each different berm width cases are provided. To show the difference in safety factors four different time steps are considered. The safety factors of the original case of Hancağız Dam, i.e. having no berm at the downstream, are indicated with bold numbers. At each increase in berm width, both of the volume of embankment and safety factor values increase together. It seems beneficial to choose the berm width of 15 m because the increase in safety factor is four times the increase in embankment volume.

Table 4-32: Variation of safety factor of downstream slope and embankment volume for different downstream berm widths in rapid drawdown condition

Time (days)	**Safety Factor for No Berm**	Safety Factor for t_b=3 m	Difference of Safety Factor	Difference of Volume	Safety Factor for t_b=7 m	Difference of Safety Factor	Difference of Volume	Safety Factor for t_b=10 m	Difference of Safety Factor	Difference of Volume	Safety Factor for t_b=15 m	Difference of Safety Factor	Difference of Volume
1	**1.49**	1.53	2.5%	0.7%	1.58	6.1%	1.7%	1.59	6.9%	2.5%	1.71	14.6%	3.7%
11	**1.48**	1.51	2.6%		1.56	5.8%		1.58	6.9%		1.68	13.9%	
21	**1.47**	1.51	2.7%		1.56	5.6%		1.58	7.0%		1.68	13.7%	
40	**1.47**	1.52	3.4%		1.56	5.7%		1.58	7.4%		1.68	14.0%	

The effect of the height of the downstream berm on safety factor of the upstream slope is analyzed for rapid fill condition. Factor of safety values during 100 days are given in Figure 4-37 for cases of different berm height. Time-dependent safety factors are observed to be satisfactory. It can be said that there are no big differences in lines in Figure 4-37. Hence, in rapid fill condition, increasing height of the berm at the downstream slope of the dam, does not affect safety factors of the upstream slope.

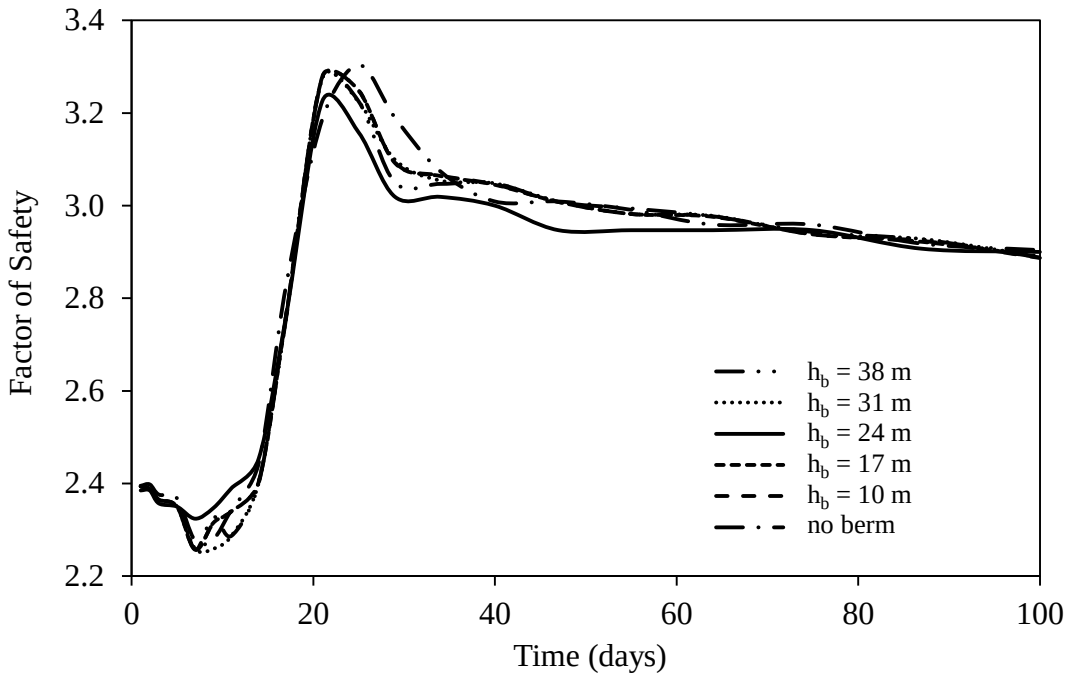


Figure 4-37: Variation of safety factor of upstream slope with respect to time for different downstream berm heights in rapid fill condition

In Table 4-33, the variation of embankment volume per unit width and safety factors of each different berm height cases are provided. To show the difference in safety factors four different time steps are considered. In this table, the safety factors of the original case of Hancağız Dam, i.e. having no berm at the downstream, are indicated with bold numbers. At each increase in berm height, only the embankment volume increases, whereas safety factor values do not change remarkably.

Table 4-33: Variation of safety factor of upstream slope and embankment volume for different downstream berm heights in rapid drawdown condition

Time (days)	**Safety Factor for No Berm**	Safety Factor for h_b=10 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=17 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=24 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=31 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=38 m	Difference of Safety Factor	Difference of Volume
1	**2.40**	2.39	0.0%	1.0%	2.39	0.0%	1.7%	2.39	-0.4%	2.4%	2.39	0.0%	4.1%	2.39	0.0%	4.9%
11	**2.34**	2.34	-0.2%		2.34	-0.2%		2.39	2.0%		2.29	-2.4%		2.29	-2.3%	
21	**3.19**	3.28	2.9%		3.28	2.9%		3.23	1.2%		3.28	2.8%		3.28	-0.1%	
40	**3.01**	3.05	1.2%		3.05	1.2%		3.00	-0.3%		3.05	1.3%		3.05	0.1%	

The effect of the number of the berms on safety factor of the upstream slope is analyzed for rapid fill condition when the berm is at the downstream slope of the dam. For cases of different berm number, factor of safety values during 100 days, are given in Figure 4-38. According to the Figure 4-38, there is no abrupt variation in lines. Time-dependent safety factors are observed to be satisfactory. So it can be said that increasing the number of the berms at the downstream slope of the dam, does not affect safety factors for the upstream slope.

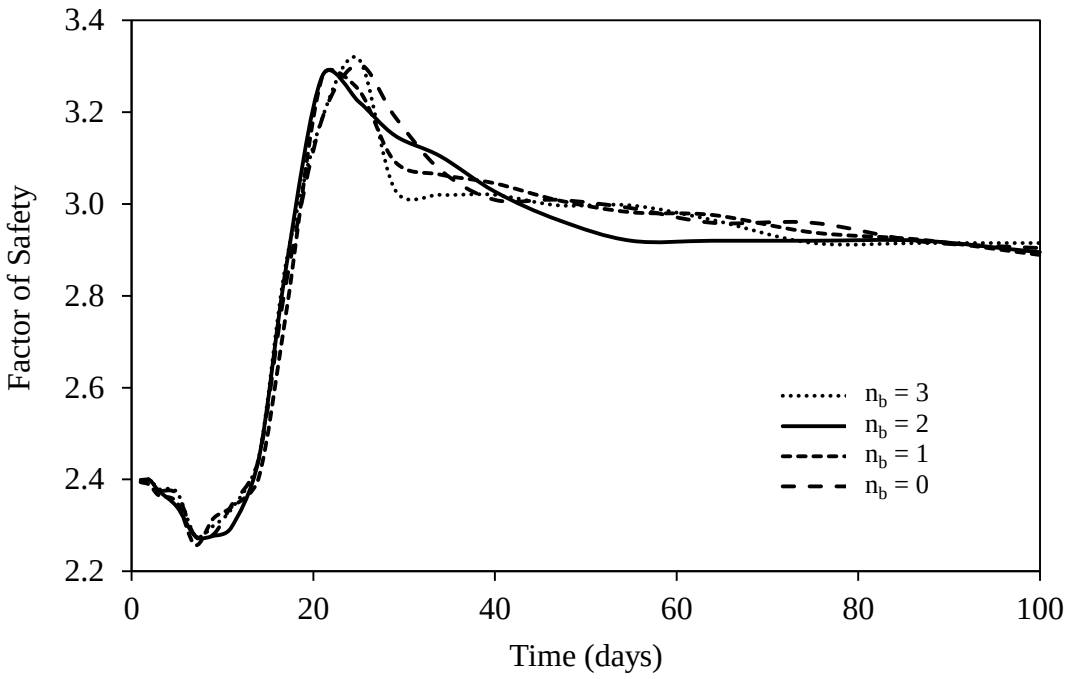


Figure 4-38: Variation of safety factor of upstream slope with respect to time for different downstream berm numbers in rapid fill condition

In Table 4-34, the variation of embankment volume per unit width and safety factors of each different berm number cases are provided. To show the difference in safety factors four different time steps are considered. In this table, the safety factors of the original case of Hancağız Dam, i.e. having no berm at the downstream are indicated with bold numbers. At each increase in berm number, only the embankment volume increases, whereas safety factor values do not change significantly.

Table 4-34: Variation of safety factor of upstream slope and embankment volume for different downstream berm numbers in rapid fill condition

Time (days)	**Safety Factor for n_b=0**	Safety Factor for n_b=1	Difference of Safety Factor	Difference of Volume	Safety Factor for n_b=2	Difference of Safety Factor	Difference of Volume	Safety Factor for n_b=3	Difference of Safety Factor	Difference of Volume
1	**2.40**	2.39	0.0%	1.7%	2.40	0.2%	2.9%	2.40	0.0%	6.0%
11	**2.34**	2.34	-0.2%		2.30	-2.0%		2.34	-0.3%	
21	**3.19**	3.28	2.9%		3.28	2.9%		3.19	0.0%	
40	**3.01**	3.05	1.2%		3.03	0.6%		3.02	0.4%	

The effect of the width of the downstream berm on safety factor of the upstream slope is analyzed for rapid fill condition. In cases of different berm widths factor of safety values for 100 days, are shown in Figure 4-39. Time-dependent safety factors are observed to be satisfactory. Despite the fact that after eightieth day, divergence in lines is seen in Figure 4-39. In general, it can be said that increasing width of the downstream berm, does not affect the safety factors for the upstream slope in rapid fill condition.

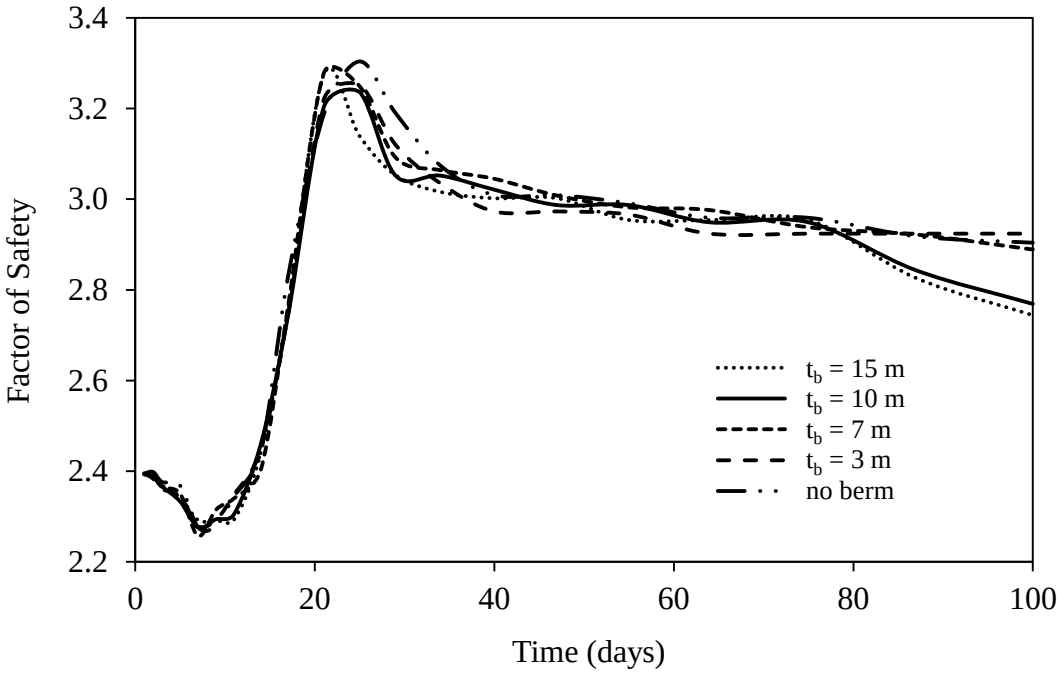


Figure 4-39: Variation of safety factor of upstream slope with respect to time for different downstream berm widths in rapid fill condition

In Table 4-35, the variation of embankment volume per unit width and safety factors of each different berm width cases are provided. To show the difference in safety factors four different time steps are considered. Safety factors of the original case of Hancağız Dam, i.e. having no berm at the downstream, are indicated with bold numbers. At each increase in berm width, only the embankment volume increases, whereas safety factor values do not change remarkably.

Table 4-35: Variation of safety factor of upstream slope and embankment volume for different downstream berm widths in rapid fill condition

Time (days)	**Safety Factor for No Berm**	Safety Factor for t_b=3 m	Difference of Safety Factor	Difference of Volume	Safety Factor for t_b=7 m	Difference of Safety Factor	Difference of Volume	Safety Factor for t_b=10 m	Difference of Safety Factor	Difference of Volume	Safety Factor for t_b=15 m	Difference of Safety Factor	Difference of Volume
1	**2.40**	2.40	0.0%	0.7%	2.39	0.0%	1.7%	2.39	-0.1%	2.5%	2.39	-0.1%	3.7%
11	**2.34**	2.35	0.2%		2.34	-0.2%		2.31	-1.7%		2.29	-2.2%	
21	**3.19**	3.22	1.0%		3.28	2.9%		3.20	0.5%		3.28	2.8%	
40	**3.01**	2.97	-1.2%		3.05	1.2%		3.02	0.4%		3.00	-0.2%	

The effect of the height of the berm on safety factor of the downstream slope is analyzed for rapid fill condition when the berm is at the downstream face of the dam. Factor of safety values are shown in Figure 4-40 for cases of different berm heights. Time-dependent safety factors are observed to be satisfactory. A different graph is drawn to see differences clearly in cases of varied berm height (see Figure 4-41). In rapid fill condition, increasing the downstream berm height provides higher safety factors of downstream slope of the dam until the ratio of berm height to dam height is 0.66. However, after this ratio exceeds 0.66, increasing the downstream berm height causes lower safety factors for the downstream slope in rapid fill condition.

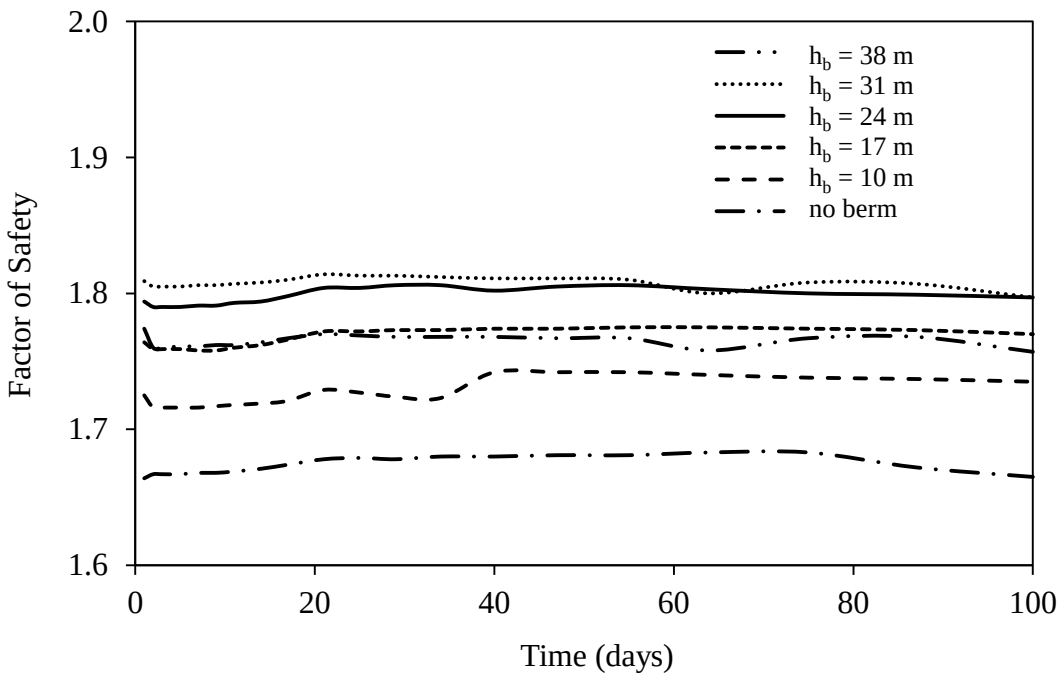


Figure 4-40: Variation of safety factor of downstream slope with respect to time for different downstream berm heights in rapid fill condition

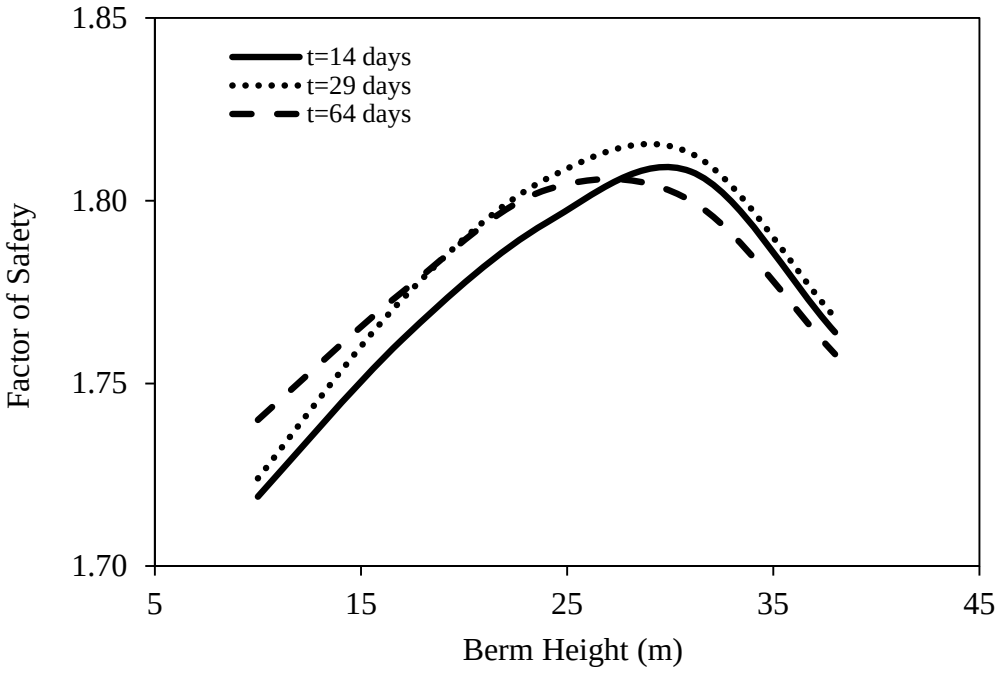


Figure 4-41: Variation of safety factor of downstream slope with respect to downstream berm height in rapid fill condition

In Table 4-36, the variation of embankment volume per unit width and safety factors of each different berm height cases are provided. To show the difference in safety factors four different time steps are considered. Safety factors of the original case of Hancağız Dam, i.e. having no berm at the downstream, are indicated with bold numbers. At each increase in berm height, both of the volume of embankment and safety factor values increase together. But after a critical point, safety factor begins to decrease with increasing berm height and this critical point is can be seen in Figure 4-41. It makes sense to choose the value of berm height, such that the ratio of berm height to dam height becomes 0.60.

Table 4-36: Variation of safety factor of downstream slope and embankment volume for different downstream berm heights in rapid fill condition

Time (days)	**Safety Factor for No Berm**	Safety Factor for h_b=10 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=17 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=24 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=31 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=38 m	Difference of Safety Factor	Difference of Volume
1	**1.66**	1.73	3.7%	1.0%	1.76	6.0%	1.7%	1.79	7.8%	2.4%	1.81	8.7%	4.1%	1.77	2.8%	4.9%
11	**1.67**	1.72	2.9%		1.76	5.5%		1.79	7.4%		1.81	8.3%		1.76	2.6%	
21	**1.68**	1.73	3.0%		1.77	5.6%		1.80	7.5%		1.81	8.1%		1.77	2.4%	
40	**1.68**	1.74	3.7%		1.77	5.6%		1.80	7.3%		1.81	7.8%		1.77	1.5%	

The effect of the width of the berm on safety factor of downstream slope is analyzed for steady-state seepage condition when the berm is at the downstream slope of the dam. For cases of different berm width, safety factors are shown in Figure 4-42. In this figure, it is obvious that increasing the number of the berms at the downstream slope of the dam, provides higher safety factors for the downstream slope of the dam in rapid fill condition.

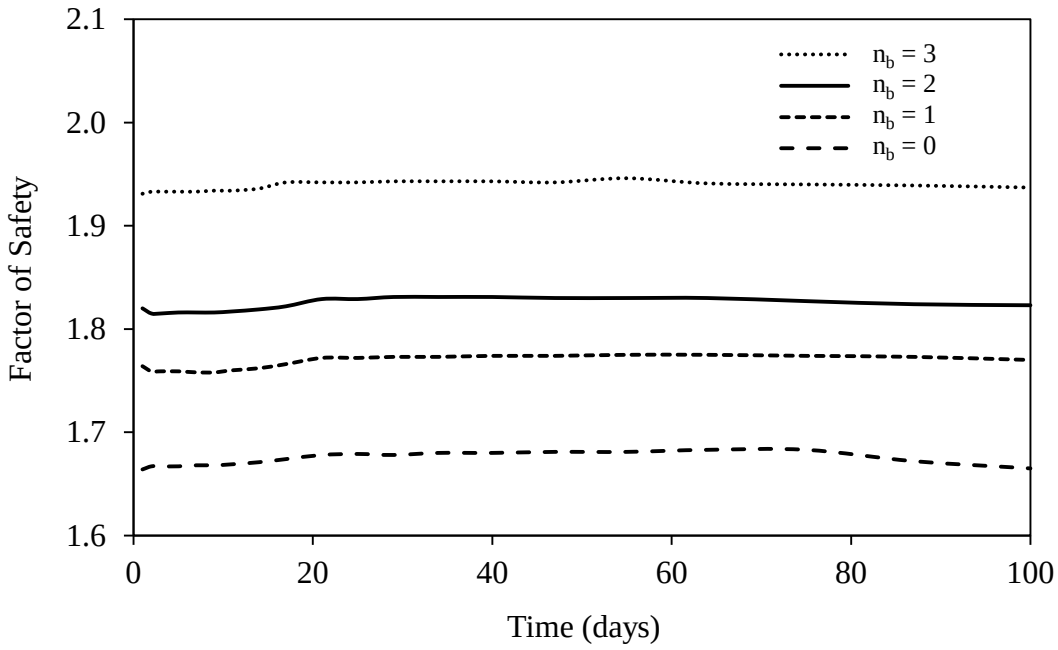


Figure 4-42: Variation of safety factor of downstream slope with respect to time for different downstream berm numbers in rapid fill condition

In Table 4-37, the variation of embankment volume per unit width and safety factors of each different berm number cases are provided. To show the difference in safety factors, four different time steps are considered. Safety factors of the original case of Hancağız Dam, i.e. having no berm at downstream, are indicated with bold numbers. At each increase in berm number, both of the volume of embankment and safety factor values increase together. It seems better that the dam has one berm at the downstream slope since the increase in safety factor is three times the increase in embankment volume.

Table 4-37: Variation of safety factor of downstream slope and embankment volume for different downstream berm numbers in rapid fill condition

Time (days)	**Safety Factor for n_b=0**	Safety Factor for n_b=1	Difference of Safety Factor	Difference of Volume	Safety Factor for n_b=2	Difference of Safety Factor	Difference of Volume	Safety Factor for n_b=3	Difference of Safety Factor	Difference of Volume
1	**1.66**	1.76	6.0%	1.7%	1.82	9.4%	2.9%	1.93	16.0%	6.0%
11	**1.67**	1.76	5.5%		1.82	8.9%		1.93	15.9%	
21	**1.68**	1.77	5.6%		1.83	9.0%		1.94	15.7%	
40	**1.68**	1.77	5.6%		1.83	9.0%		1.94	15.7%	

The effect of the width of the berm on safety factor of the downstream slope is analyzed for rapid fill condition. Safety factors are shown in Figure 4-43 for cases of different berm widths. Increasing the downstream berm width, provides higher safety factors for the downstream slope of the dam in rapid fill condition as seen in Figure 4-43.

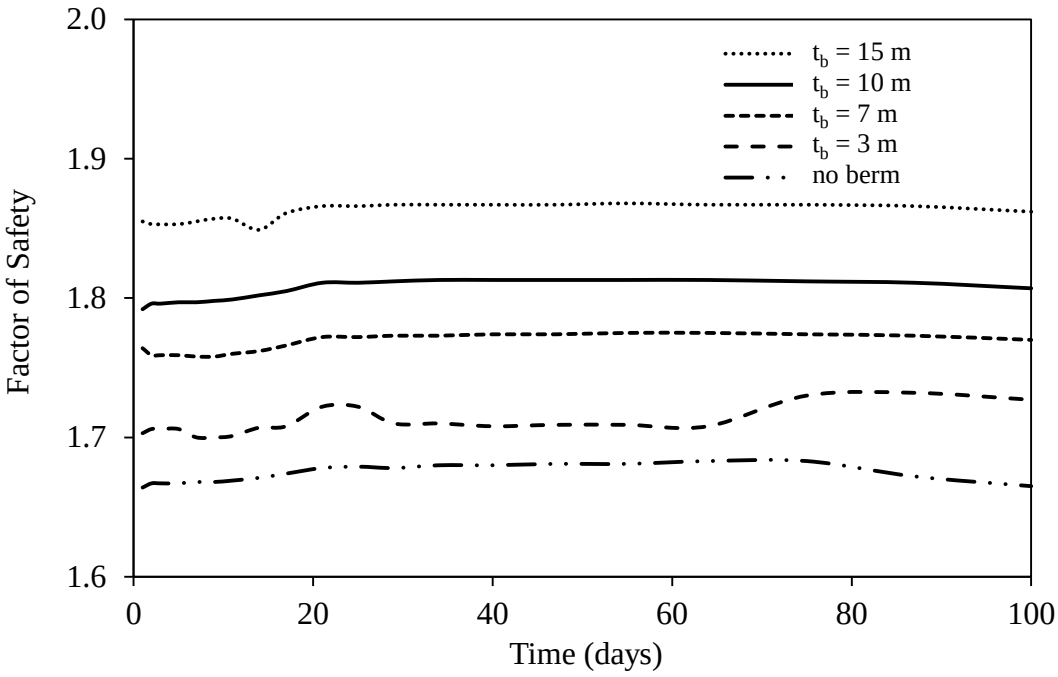


Figure 4-43: Variation of safety factor of downstream slope with respect to time for different downstream berm widths in rapid fill condition

In Table 4-38, the variation of embankment volume per unit width and safety factors of each different berm width cases are provided. To show the difference in safety factors four different time steps are considered. Safety factors of the original case of Hancağız Dam, i.e. having no berm at downstream, are indicated with bold numbers. At each increase in berm width, both of the volume of the embankment and safety factor values increase together. Choosing the berm width of 7 m is preferable because the increase in safety factor is three times the increase in embankment volume.

Table 4-38: Variation of safety factor of downstream slope and embankment volume for different downstream berm widths in rapid fill condition

Time (days)	**Safety Factor for No Berm**	Safety Factor for t_b=3 m	Difference of Safety Factor	Difference of Volume	Safety Factor for t_b=7 m	Difference of Safety Factor	Difference of Volume	Safety Factor for t_b=10 m	Difference of Safety Factor	Difference of Volume	Safety Factor for t_b=15 m	Difference of Safety Factor	Difference of Volume
1	**1.66**	1.70	2.3%	0.7%	1.76	6.0%	1.7%	1.79	7.7%	2.5%	1.86	11.5%	3.7%
11	**1.67**	1.70	1.9%		1.76	5.5%		1.80	7.8%		1.86	11.3%	
21	**1.68**	1.72	2.6%		1.77	5.6%		1.81	7.9%		1.87	11.2%	
40	**1.68**	1.71	1.7%		1.77	5.6%		1.81	7.9%		1.87	11.1%	

The effect of the height of the downstream berm on safety factor of the upstream slope is analyzed for steady-state seepage condition. For cases of different berm heights, safety factors are given in Figure 4-44. In lines, some fluctuations are seen, nevertheless it can be said that in steady-state seepage condition, increasing height of the berm at downstream slope of the dam does not affect safety factors for the upstream slope.

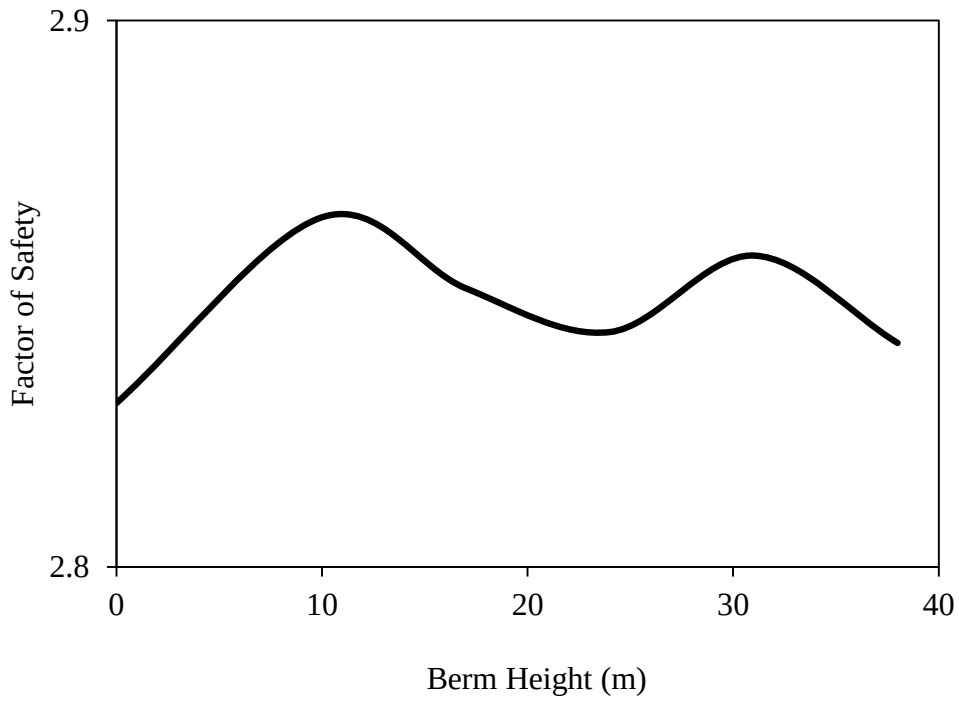


Figure 4-44: Variation of safety factor of upstream slope with respect to downstream berm height in steady-state seepage condition

In Table 4-39, the variation of embankment volume per unit width and safety factors of each different berm height cases are provided. The safety factors of the original case of Hancağız Dam, i.e. having no berm at the downstream, are indicated with bold numbers. Safety factors do not change significantly with increasing embankment volume.

Table 4-39: Variation of safety factor of upstream slope and embankment volume for different downstream berm heights in steady-state seepage condition

Safety Factor for No Berm	Safety Factor for h_b=10 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=17 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=24 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=31 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=38 m	Difference of Safety Factor	Difference of Volume
2.83	2.86	1.20%	1.13%	2.85	0.74%	1.81%	2.84	0.46%	2.61%	2.86	0.95%	3.41%	2.84	0.39%	4.19%

The effect of the number of the downstream berms on safety factor of the upstream slope is analyzed for steady-state seepage condition. For cases of different berm numbers, factor of safety values are given in Figure 4-45. In steady-state seepage condition, increasing number of the berms at the downstream slope of the dam does not affect safety factors for the upstream slope.

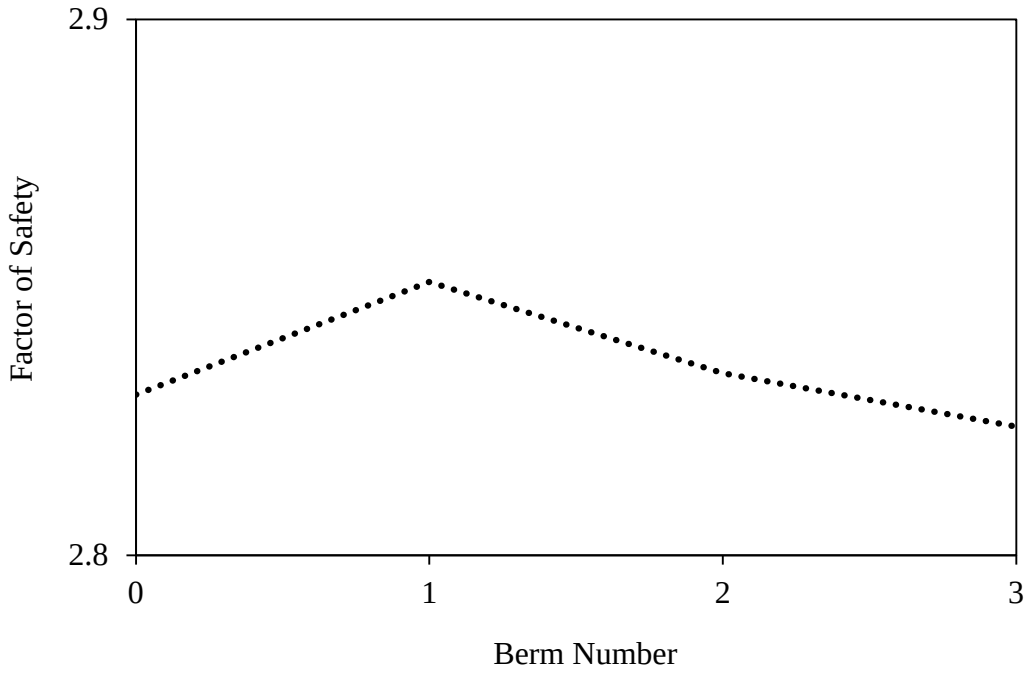


Figure 4-45: Variation of safety factor of upstream slope with respect to downstream berm number in steady-state seepage condition

In Table 4-40, the variation of embankment volume per unit width and safety factors of each different berm number cases are provided. The safety factors of the original case of Hancağız Dam, i.e. having no berm at downstream, are indicated with bold numbers. Safety factors do not change remarkably with increasing embankment volume.

Table 4-40: Variation of safety factor of upstream slope and embankment volume for different downstream berm numbers in steady-state seepage condition

Safety Factor for n_b=0	Safety Factor for n_b=1	Difference of Safety Factor	Difference of Volume	Safety Factor for n_b=2	Difference of Safety Factor	Difference of Volume	Safety Factor for n_b=3	Difference of Safety Factor	Difference of Volume
2.83	2.85	0.74%	1.13%	2.83	0.14%	3.38%	2.82	-0.21%	6.80%

The effect of the width of the berm on safety factor of the upstream slope is analysed for steady-state seepage condition. The downstream berm width is varied. For cases of different berm widths factor of safety values are shown in Figure 4-46. It can be said that in steady-state seepage condition, increasing the width of the downstream berm, does not affect safety factors for the upstream slope.

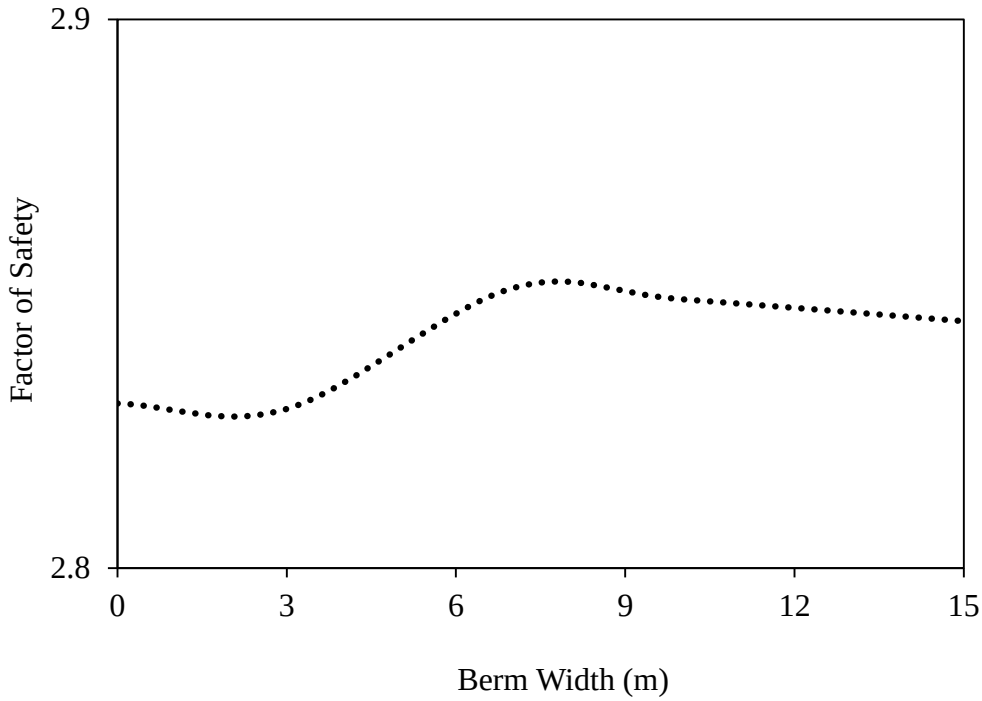


Figure 4-46: Variation of safety factor of upstream slope with respect to downstream berm width in steady-state seepage condition

In Table 4-41, the variation of embankment volume per unit width and safety factors of each different berm width cases are provided. Safety factors do not change notably with increasing embankment volume.

Table 4-41: Variation of safety factor of upstream slope and embankment volume for different downstream berm widths in steady-state seepage condition

Safety Factor for No Berm	Safety Factor for t_b=3 m	Difference of Safety Factor	Difference of Volume	Safety Factor for t_b=7 m	Difference of Safety Factor	Difference of Volume	Safety Factor for t_b=10 m	Difference of Safety Factor	Difference of Volume	Safety Factor for t_b=15 m	Difference of Safety Factor	Difference of Volume
2.83	2.83	-0.04%	0.74%	2.85	0.74%	1.81%	2.85	0.67%	2.61%	2.85	0.53%	3.95%

The effect of the height of the berm on safety factor of the downstream slope is analysed for steady-state seepage condition. The downstream berm height is altered. For cases of different berm heights factor of safety values are given in Figure 4-47. It is clear that in steady-state seepage condition, increasing the downstream berm height, provides higher safety factors for the downstream slope of the dam until the ratio of berm height to dam height is 0.66. However, after this ratio exceeds 0.66, increasing the downstream berm height causes lower safety factors of the downstream slope in steady-state seepage condition. This result is obtained by the analysis type of Sigma/W Stress.

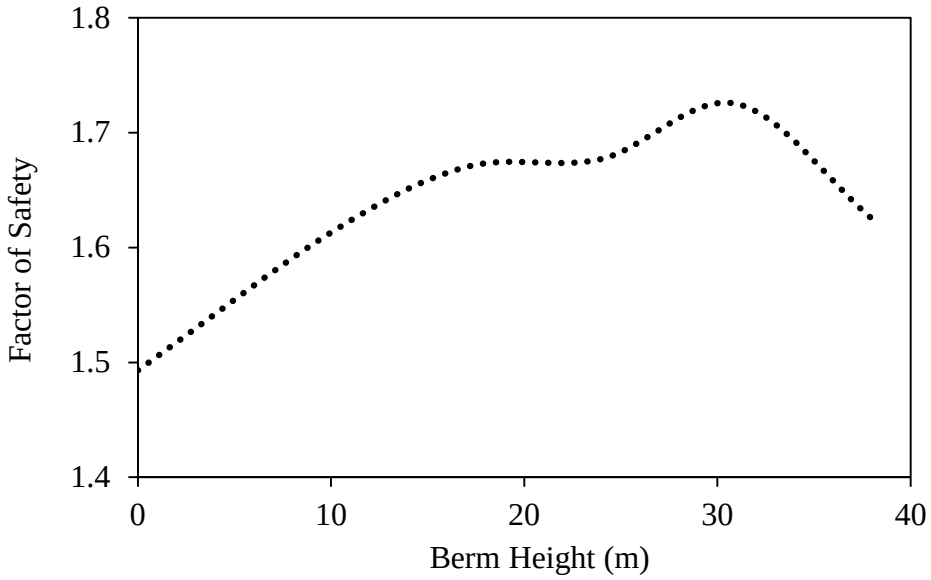


Figure 4-47: Variation of safety factor of downstream slope with respect to downstream berm height in steady-state seepage condition

In Table 4-42, the variation of embankment volume per unit width and safety factors of each different berm height cases are provided. At each increase in berm height, both of the embankment volume and safety factor values increase together. But after a critical point, safety factor begins to decrease with increasing berm height and this critical point can be seen in Figure 4-47. It makes sense to choose the value of berm height such that the ratio of berm height to dam height becomes 0.60.

Table 4-42: Variation of safety factor of downstream slope and embankment volume for different downstream berm heights in steady-state seepage condition

Safety Factor for No Berm	Safety Factor for h_b=10 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=17 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=24 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=31 m	Difference of Safety Factor	Difference of Volume	Safety Factor for h_b=38 m	Difference of Safety Factor	Difference of Volume
1.49	1.61	8.0%	1.1%	1.67	11.9%	1.8%	1.68	12.3%	2.6%	1.73	15.5%	3.4%	1.63	8.8%	4.2%

The effect of the number of the berms on safety factor of downstream slope is analyzed for steady-state seepage condition. For cases of different berm number, factor of safety values, are shown in Figure 4-48. In steady-state seepage condition, increasing number of the berm at the downstream face of the dam, provides higher safety factors for the downstream slope of the dam. However, almost no difference is observed between one berm and two berms cases.

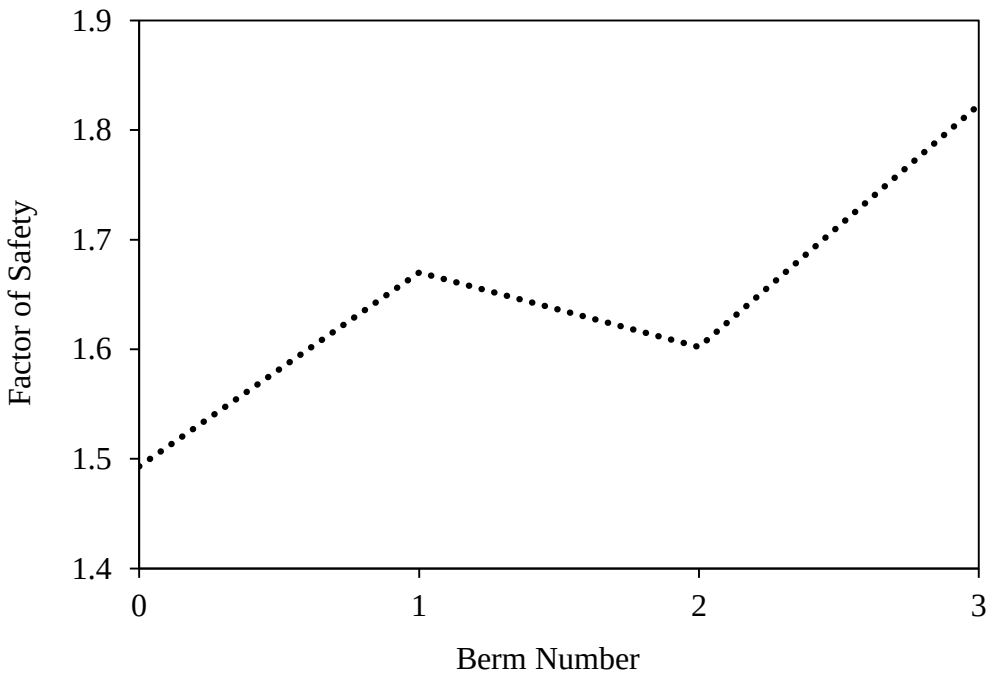


Figure 4-48: Variation of safety factor of downstream slope with respect to downstream berm number in steady-state seepage condition

In Table 4-43, the variation of embankment volume and safety factors of each different berm number cases are provided. At each increase in berm number, both of the embankment volume and safety factor values increase together. According to Sigma/W Stress, to have three berms is more beneficial since it provides an increase of 22.1% in safety factor with an increase of 6.8% in embankment volume.

Table 4-43: Variation of safety factor of downstream slope and embankment volume for different downstream berm numbers in steady-state seepage condition

Safety Factor for n_b=0	Safety Factor for n_b=1	Difference of Safety Factor	Difference of Volume	Safety Factor for n_b=2	Difference of Safety Factor	Difference of Volume	Safety Factor for n_b=3	Difference of Safety Factor	Difference of Volume
1.49	1.67	1.09%	1.13%	1.60	7.30%	3.38%	1.82	22.10%	6.80%

The effect of the width of the berm on safety factor of the downstream slope is analysed for steady-state seepage condition. For cases of different downstream berm widths, factor of safety values are shown in Figure 4-49. In steady-state seepage condition, increasing the width of the berm at the downstream slope of the dam, provides higher safety factors for the downstream slope of the dam.

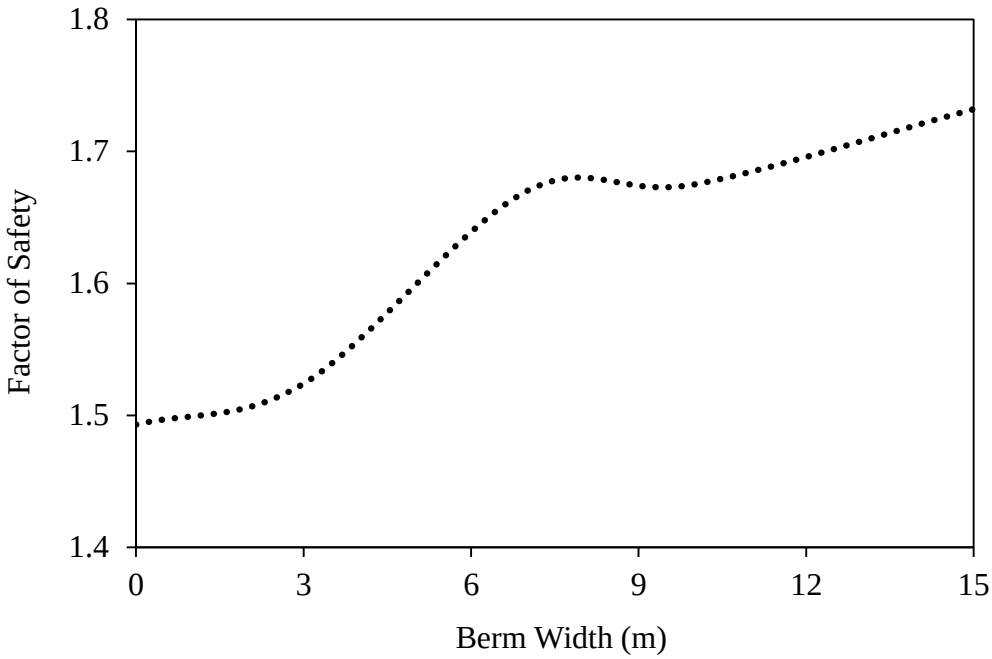


Figure 4-49: Variation of safety factor of downstream slope with respect to downstream berm width in steady-state seepage condition

In Table 4-44, the variation of embankment volume per unit width and safety factors of each different berm width cases are provided. At each increase in berm width, both of the embankment volume and safety factor values increase together. According to this table, choosing berm width of 7 m is more rational since it provides an increase by 11.86% in safety factor with an increase of 1.81% in embankment volume.

Table 4-44: Variation of safety factor of downstream slope and embankment volume for different downstream berm widths in steady-state seepage condition

Safety Factor for No Berm	Safety Factor for t_b=3 m	Difference of Safety Factor	Difference of Volume	Safety Factor for t_b=7 m	Difference of Safety Factor	Difference of Volume	Safety Factor for t_b=10 m	Difference of Safety Factor	Difference of Volume	Safety Factor for t_b=15 m	Difference of Safety Factor	Difference of Volume
1.49	1.52	2.08%	0.74%	1.67	11.86%	1.81%	1.68	12.19%	2.61%	1.73	16.01%	3.95%

4.4 Additional Analyses

In order to investigate, the characteristics of the slope stability of the embankment, additional analyses are done for various dam heights and rapid drawdown/fill rates. In previous analyses, it is seen that increasing the berm height up to a certain level, provides increase in slope stability. However, further increasing berm height causes decrease in safety factor for Hancağız Dam. To investigate whether this situation is valid for various dam heights, additional analyses are conducted. In the original case, Hancağız Dam has 45 m height from the thalweg. In additional analyses, the dam height is varied to 90 m and 135 m by keeping the material properties and berm width constant. However, berm height is varied proportionally to the dam height. Analyses are done for both upstream and downstream berms. Under steady-state seepage, rapid fill, and rapid drawdown conditions, safety factors are obtained for slopes which have berm on it.

Safety factors of the upstream slope when dam heights are 45 m, 90 m, 135 m are shown in Figure 4-50 for the rapid drawdown condition. When the dam height is 45 m, increasing the upstream berm height up to 66% of dam height, provided an increase in the safety factor. After this ratio, safety factor began to decrease. When the dam height is 90 m, safety factor increases with increasing upstream berm height. However, when the dam height is 135 m, safety factor does not change too much with the variation of the upstream berm height.

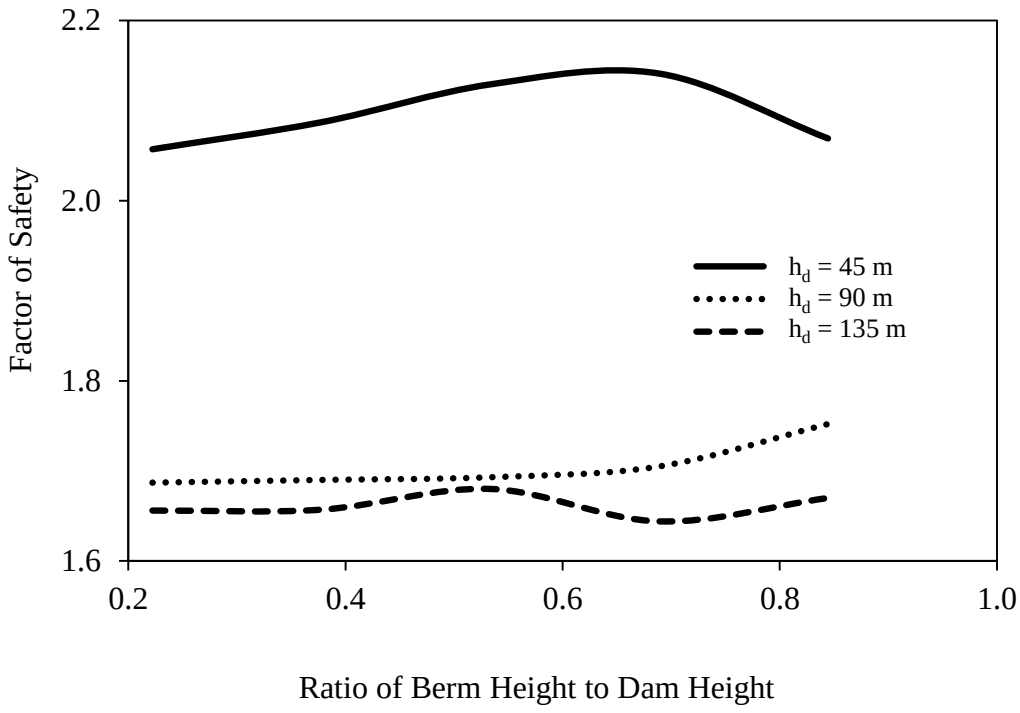


Figure 4-50: Variation of safety factor of upstream slope with respect to ratio of upstream berm height to dam height in rapid drawdown condition

In Figure 4-51, safety factors of the upstream slope are shown for rapid fill condition. When the dam height is 45 m, increasing the upstream berm height up to 55% of the dam height, provided an increase in the safety factor. After this level, safety factor begins to decrease. When the dam height is 90 m, safety factor increases with the increasing upstream berm height. On the other hand, when the dam height is 135 m, safety factor does not change significantly with the variation of the upstream berm height. But after a ratio of 0.66, safety factor begins to decrease with the increasing upstream berm height.

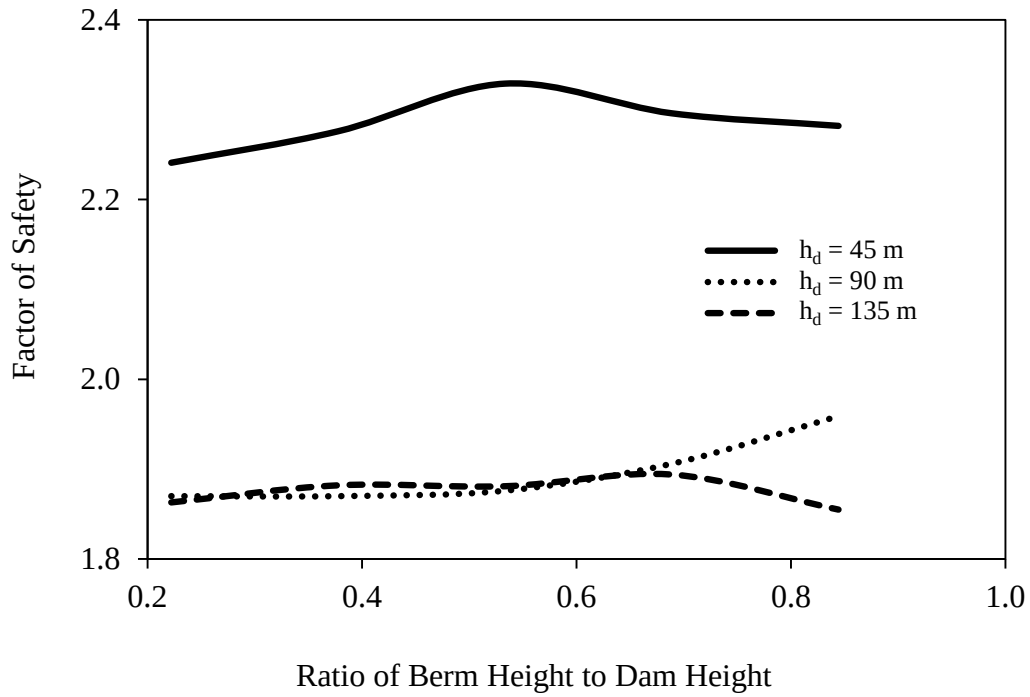


Figure 4-51: Variation of safety factor of upstream slope with respect to ratio of upstream berm height to dam height in rapid fill condition

For steady-state seepage condition, safety factors of the upstream slope are shown in Figure 4-52. When the dam height is 45 m, increasing the upstream berm height up to 66% of the dam height, provided increase in safety factor. After this level, safety factor begins to decrease. When the dam height is 90 m, safety factor does not change up to a ratio of 0.6. After this value, safety factor increases with the increasing upstream berm height. On the other hand, when the dam height is 135 m, safety factor does not change considerably with the variation of the upstream berm height.

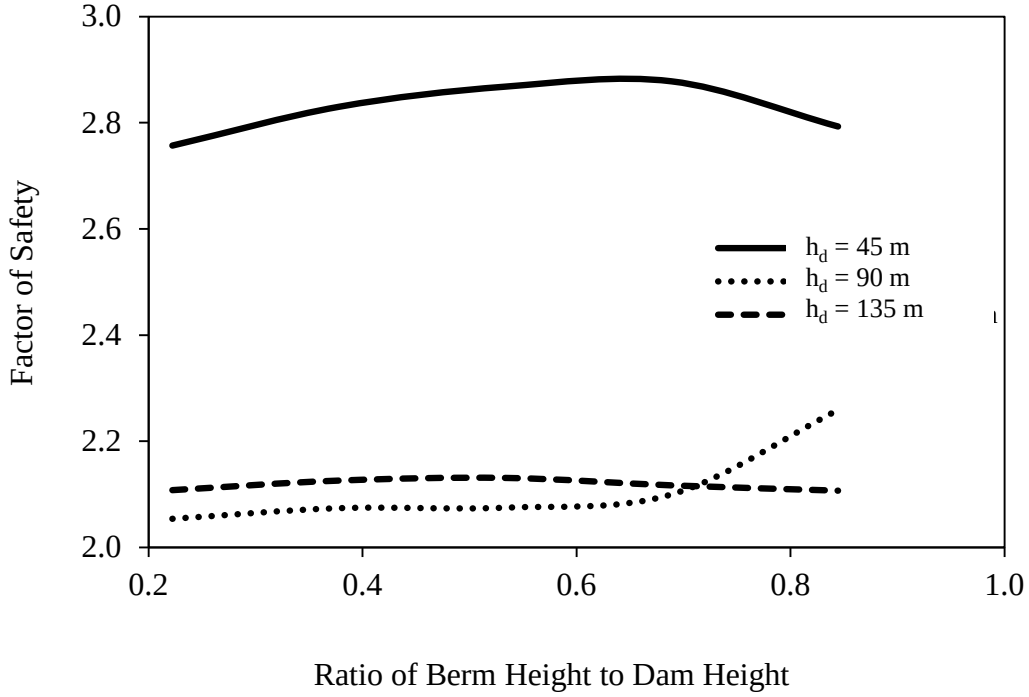


Figure 4-52: Variation of safety factor of upstream slope with respect to ratio of upstream berm height to dam height in steady-state seepage condition

In Figure 4-53, safety factors of the downstream slope are shown for the rapid drawdown condition. When the dam height is 45 m, increasing the downstream berm height up to 55% of the dam height provided an increase in safety factor. After this level, safety factor begins to decrease. When the dam height is 90 m, safety factor increases up to a ratio of 0.4. After this value, safety factor does not change with the increasing downstream berm height. On the other hand, when the dam height is 135 m, safety factor decreases up to ratio of 0.5 and after this level it begins to increase with increasing the downstream berm height. For the dam height of 135 m, critical safety factors are obtained for the ratio of berm height to dam height less than 0.6 (see Figure 4-53).

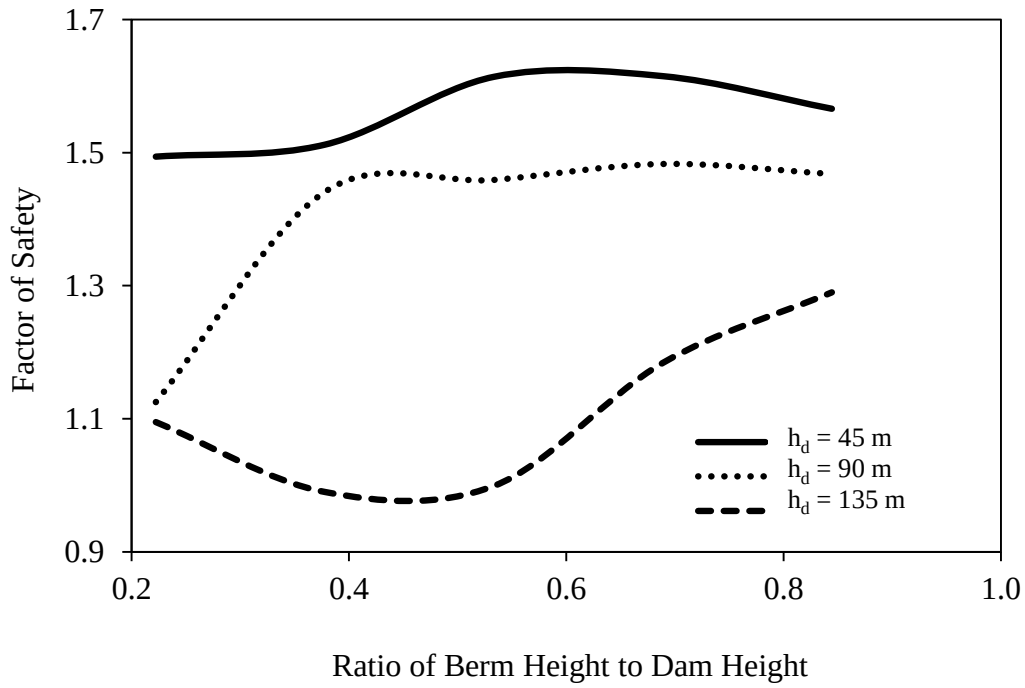


Figure 4-53: Variation of safety factor of downstream slope with respect to ratio of downstream berm height to dam height in rapid drawdown condition

Safety factors of the downstream slope are shown under rapid fill condition in Figure 4-54. When the dam height is 45 m, increasing the downstream berm height up to 66% of the dam height provides increase in safety factor. After this point, safety factor begins to decrease. When the dam heights are 90 m and 135 m, safety factors show similar tendency. But safety factors decrease with the increasing dam height.

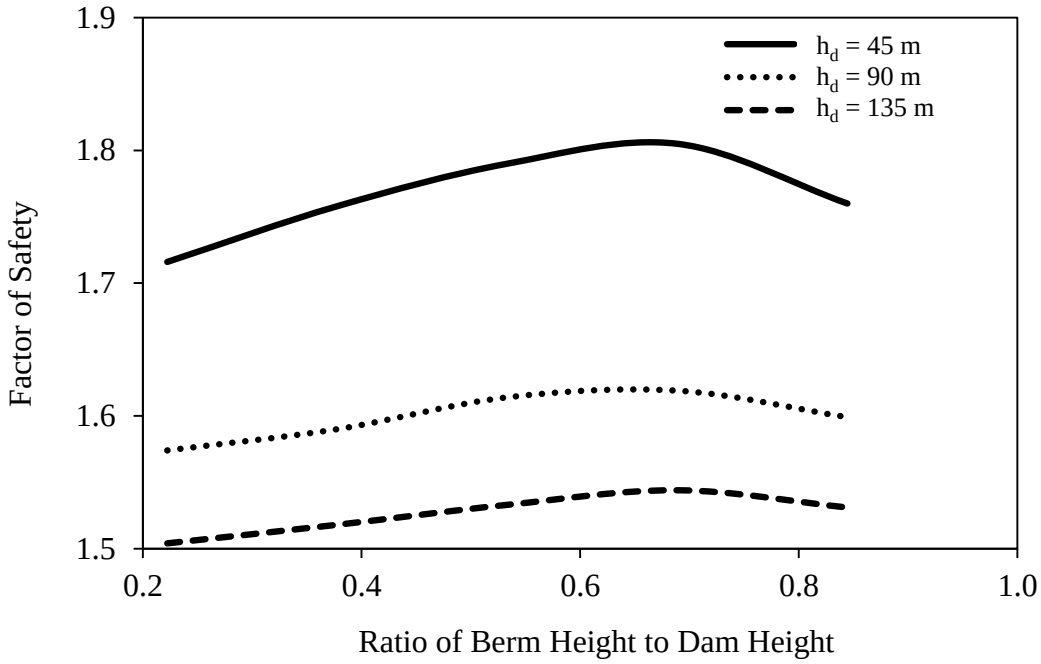


Figure 4-54: Variation of safety factor of downstream slope with respect to ratio of downstream berm height to dam height in rapid fill condition

For steady-state seepage condition, safety factors of the downstream slope are shown in Figure 4-55. When the dam height is 45 m, increasing the upstream berm height up to 66% of dam height, provided an increase in the safety factor. After this level, safety factor begins to decrease. When the dam height is 90 m, safety factor increases up to ratio of 0.4. After this value, safety factor does not change with variation of the downstream berm height. On the other hand, when dam height is 135 m, safety factor decreases up to ratio of 0.4. After this level safety factor begins to increase with increasing the downstream berm height.

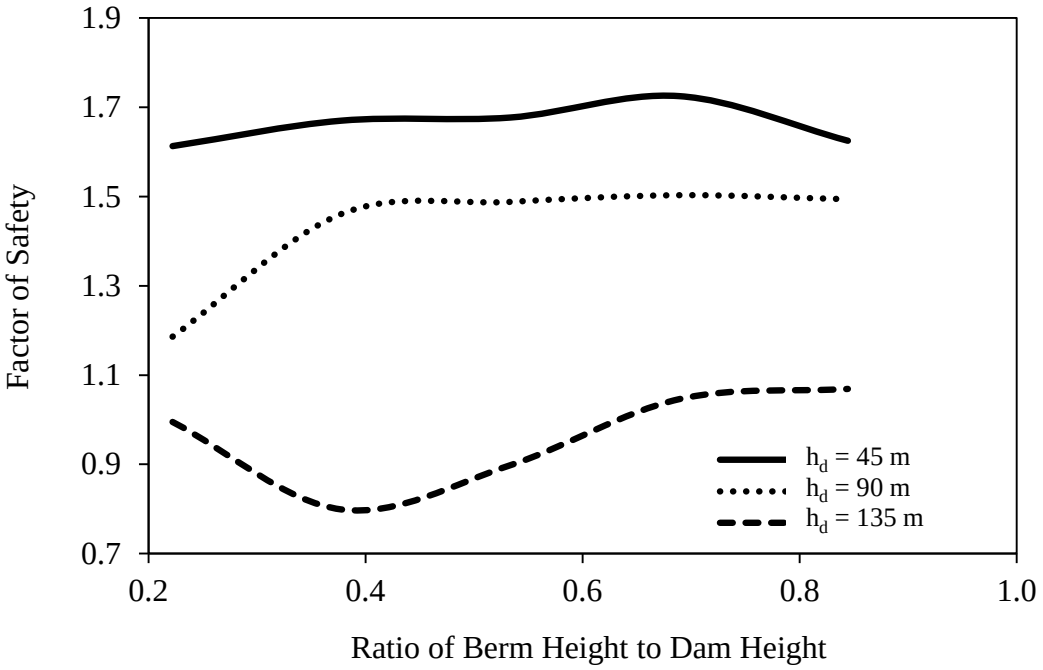


Figure 4-55: Variation of safety factor of downstream slope with respect to ratio of downstream berm height to dam height in steady-state seepage condition

In order to investigate the effect of rapid drawdown rate on slope stability, additional analyses are conducted. Rapid drawdown rates are investigated using 1 m/day, 2 m/day, 3 m/day, and 4 m/day. Safety factors of the upstream slope are presented in Figure 4-56. As it is seen in the graph, minimum values of safety factor does not change for different rapid drawdown rates and are all acceptable. But the rate of decrease diminishes with decreasing the rapid drawdown rate. This is because, the rate of decrease of pore water pressure dissipation diminishes with the decrease of rapid drawdown rate. As a result, the rate of rapid drawdown have no significant effect on the minimum and final values of the factor of safety.

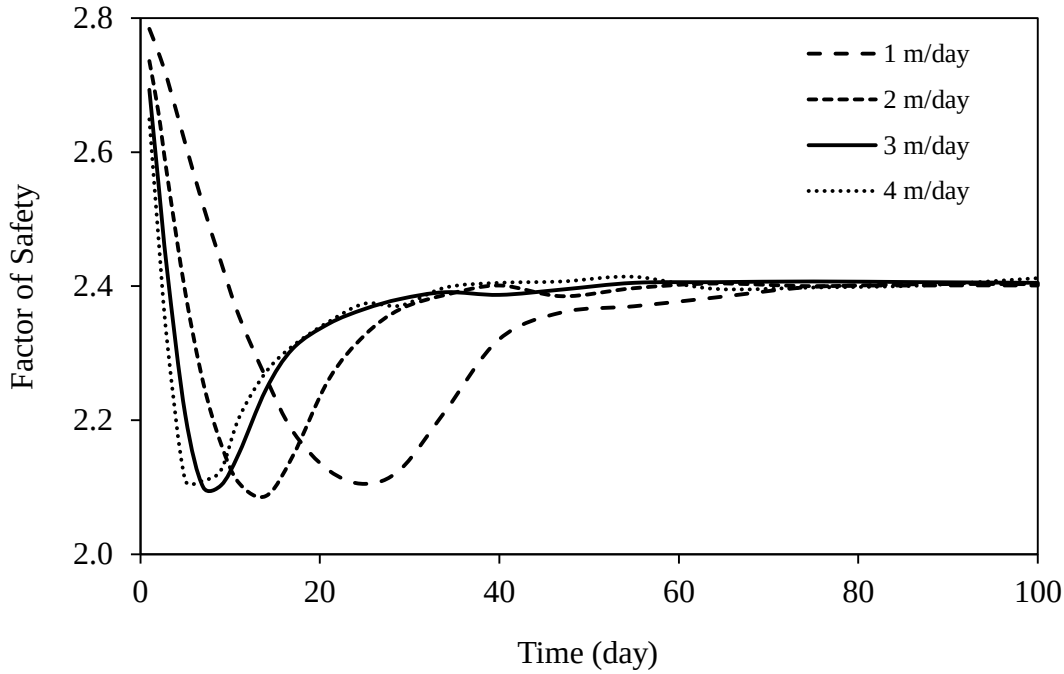


Figure 4-56: Variation of safety factor of upstream slope with respect to time for different rapid drawdown rates

In order to investigate the effect of rapid fill rate on the slope stability, additional analyses are conducted. Rapid fill rates are investigated using 1 m/day, 2 m/day, 3 m/day, and 4 m/day. Safety factors of the upstream slope are presented in Figure 4-57. As it is seen in the graph, minimum values of safety factor do not remarkably change for different rapid fill rates and are all acceptable. But the rate of increase diminishes with the decrease in the rapid fill rate. This is because, the rate of increase of pore water pressure diminishes with the decrease of the rapid fill rate. As a result, the rate of rapid fill has no significant effect on the safety factor of the upstream slope.

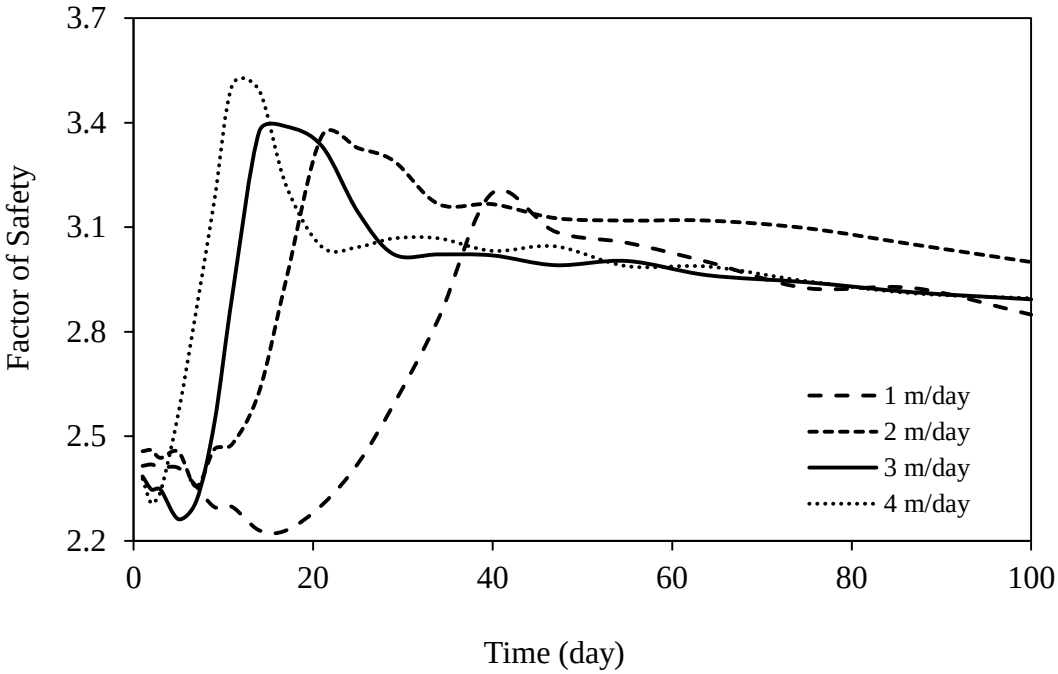


Figure 4-57: Variation of safety factor of upstream slope with respect to time for different rapid fill rates

CHAPTER 5

DISCUSSION OF RESULTS

The results showed that increasing the berm height provides an increase in the safety factor of the upstream slope under steady-state seepage, rapid fill, and rapid drawdown conditions. The reason of this situation is that increasing the berm height causes increase in the weight of the berm. Increase in the weight provides more contribution to resisting moments than driving moments in the embankment. However, after an optimum height, increasing the berm height does not increase the safety factor of the upstream slope; on the contrary it causes a decrease in the stability. This is because, increasing the berm height too much, causes extreme increase in the weight of berm. This situation results in more contribution to driving moments than resisting moments in embankment of the dam. For the rapid fill, steady-state seepage, and rapid drawdown conditions, it is found that the ratio of berm height to dam height should be in between 0.55 and 0.66 for the maximum safety factor. Similarly, Leroueil (1990) suggests that berm height should be in an interval of 40% and 50% of the dam height and results in this thesis are close to his recommendation. On the other hand, these results are obtained for a dam having a height of 45 m. If the dam height is increased, the effect of berm height on behavior of slope stability is varied. Changing the height of the upstream berm does not affect the safety factor of the downstream slope since the variation of the upstream berm height has negligible effect on pore water pressure values for the downstream slope. Similar results are obtained for the downstream berm. Namely, increasing the downstream berm height, results in an increase in the safety factor of the

downstream slope. Similar to the upstream berm, when the downstream berm height exceeds 55%-66% of the dam height, safety factor of the downstream slope begins to decrease. In addition, downstream berm does not affect the stability of the upstream slope.

To investigate the effects of upstream berm number on dam safety, berm number is varied under steady-state seepage, rapid fill, and rapid drawdown conditions. Also, the current berm is removed and then analyses are repeated. In all cases, safety factors of both upstream and downstream slopes are determined. Increasing the upstream berm number provides a rise in safety factor for the upstream slope. The reason of this situation is that increasing the berm number results in greater total berm weight. The weight of the berms act as resisting force by counter-balancing the disturbing moment on potential failure surfaces under the embankment (Chin 2005). Besides, increasing the number of the upstream berm does not affect the safety factor of the downstream slope. This is because the variation of the upstream berm number does not alter pore water pressure values for the downstream slope. Similar analyses are carried out by adding a new berm on the downstream face of the dam and varying its number. Similar findings for the downstream berm are observed, namely, increasing the downstream berm number, results in an increase in the safety factor of the downstream slope. Furthermore, it is found that the downstream berm does not affect the stability of the upstream slope.

The effect of berm width on safety factor of slope is investigated for various berm widths. For the steady-state seepage, rapid fill, and rapid drawdown conditions, safety factors of both upstream and downstream slopes are determined. Increasing the upstream berm width provides a rise in the safety factor of the upstream slope. As can be seen in Figure 5-1, the reason of this situation is that increasing the berm width lengthens the failure surface and extends the moment arm in embankment (Araya 2000). In addition, increasing the berm width, contributes to resisting moments, thus higher safety factors are obtained. In other respects, altering the width of the upstream berm does not affect the safety factor of the downstream

slope. The reason is that changing the upstream slope conditions has no influences on pore water pressures of the downstream slope. After adding a new berm on the downstream slope, it is seen that increasing the downstream berm width, results in an increase in the safety factor of the downstream slope. Besides, the downstream berm does not affect the stability of the upstream slope.

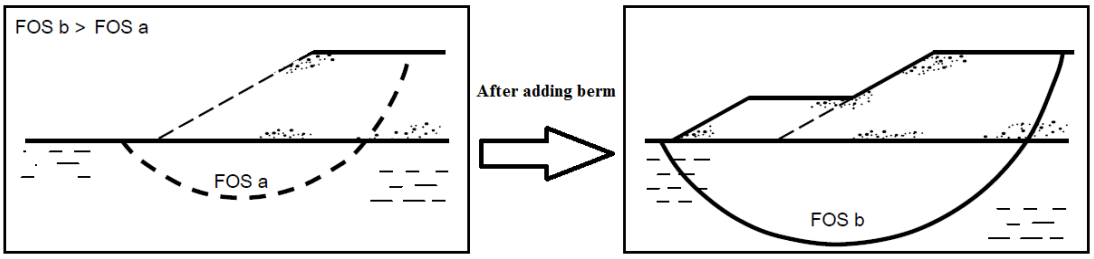


Figure 5-1: Increasing the length of potential failure surface after adding berm (adopted from Chin 2005)

In Table 5-1, a summary of all cases results are shown for steady-state seepage, rapid fill, and rapid drawdown conditions. Effects of upstream and downstream berms on the safety factor of upstream and downstream slopes are presented. In this table, "+" means when berm height, number or width increases, then safety factor increases. The minus sign, "-" means when the berm height, number or width increases then safety factor decreases. "o" means when the berm height, number or width increases safety factor does not change. In Table 5-1, "0.55" and "0.66" indicate ratios of berm height to dam height. For example, in rapid drawdown condition, increasing the upstream berm height, up to 66% of the dam height, results in increase in safety factor of the upstream slope and this situation does not affect safety factor of the downstream slope.

Recommended factor of safety values for rapid drawdown and steady-state seepage conditions are given in Table 2-1 and 2-2. The results which were obtained from the analyses for the original case of Hancağız Dam, are higher than the minimum values which are given in Table 2-1 and 2-2. For this reason, the results for the original case, are acceptable for slope stability.

The results obtained in section 4.3 are valid for Hancağız Dam which has height of 45 m. In design process of a dam, berm height, number and width should be determined according to both of the cost and stability analyses.

Table 5-1: Summary of results

			Upstream Slope	**Downstream Slope**
Upstream Berm	**Rapid Drawdown**	Berm Height	+ / 0.66 / -	o
		Berm Number	+	o
		Berm Width	+	o
	Rapid Fill	Berm Height	+ / 0.55 / -	o
		Berm Number	+	o
		Berm Width	+	o
	Steady-State Seepage	Berm Height	+ / 0.66 / -	o
		Berm Number	+	o
		Berm Width	+	o
Downstream Berm	**Rapid Drawdown**	Berm Height	o	+ / 0.55 / -
		Berm Number	o	+
		Berm Width	o	+
	Rapid Fill	Berm Height	o	+ / 0.66 / -
		Berm Number	o	+
		Berm Width	o	+
	Steady-State Seepage	Berm Height	o	+ / 0.66 / -
		Berm Number	o	+
		Berm Width	o	+

Additional analyses for different dam heights show that slope stability changes with the variation of the dam height. This is because weight of the slope increases while the dam height increases. For this reason driving and resisting moments in the dam embankment vary.

CHAPTER 6

CONCLUSIONS

6.1 Summary

In this study, effects of berm characteristics on slope stability of earth-fill dams are investigated. The height, number and width of the berm on the upstream face of Hancağız Dam, Turkey, are varied to examine the effects of berm properties on the dam safety. In addition, a new berm is added to the downstream face and the same procedures are applied for it. All analyses are conducted for three critical hydraulic conditions, which are rapid drawdown, steady-state seepage, and rapid fill. The pore water pressures and seepage rates in dam embankment are determined by SEEP/W software; whereas the stress distributions are obtained by using SIGMA/W software. Safety factors of the upstream and downstream slopes are calculated by using SLOPE/W software.

6.2 Major Findings of the Study

The following conclusions are drawn from this study:

- Safety factor of the upstream slope decreases while water level is lowering in rapid drawdown condition. After safety factor drops to a minimum value, it increases with the decrease of pore water pressure. Then safety factor continues at a constant value since pore water pressures dissipate in the

upstream zone. As a result, the rapid drawdown is a critical condition for the upstream slope. On the other hand, rapid drawdown condition is not critical for stability of the downstream slope.

- In rapid fill condition, safety factor of the upstream slope increases while water level is rising. After safety factor reaches to a maximum value, it decreases with the increase of pore water pressure. Then the safety factor continues at a constant value since pore water pressures reach to the maximum level in upstream zone. Namely, the rapid fill is a critical condition for the upstream slope but it is not critical for stability of the downstream slope.

- In the steady-state seepage condition, there is no critical situation for the upstream slope. However, steady-state seepage condition is critical for the stability of the downstream slope. High pore water pressures near the downstream slope cause instability for the downstream slope since there is no water acting on the downstream face of the dam.

- Increasing the upstream berm height provides an increase in the safety factor of the upstream slope in the rapid drawdown, steady-state seepage, and rapid fill conditions. However, after an optimum height, increasing the upstream berm height does not increase the safety factor of the upstream slope. Conversely, it causes a decrease in the stability. For the rapid fill, steady-state seepage, and rapid drawdown conditions, the ratio of berm height to dam height should be in between 0.55 and 0.66 for the maximum safety factor. This situation is valid for the dam height of 45 m. If the dam height is increased, effects of berm height on slope stability vary.

- On the other hand, changing the height of the upstream berm does not affect safety factor of the downstream slope. Similar results are obtained for the downstream berm. Namely, increasing the downstream berm height, results

in an increase in the safety factor of the downstream slope. Similar to the upstream berm, excessive increase of downstream berm height, causes decrease in safety factor of the downstream slope. In addition, the downstream berm does not affect the stability of the upstream slope.

- The slope stability analyses showed that increasing the upstream berm number provides an increase in safety factor of the upstream slope. Besides, the variation of the number of the upstream berm does not affect the safety factor of the downstream slope. Increasing the downstream berm number, results in an increase of the safety factor for the downstream slope. Furthermore, it is found that the downstream berm does not affect the stability of the upstream slope.

- When the upstream berm width is increased, it ensures an increase in the safety factor of the upstream slope. But, increasing the width of the upstream berm does not affect the safety factor of the downstream slope. In other respects, increasing the downstream berm width, results increase in safety factor of the downstream slope. Besides, downstream berm does not affect the stability of the upstream slope.

- The above results obtained are valid for 45 m height of the dam (i.e. Hancağız Dam). The effect of different dam heights on the safety factor, pore water pressure, and seepage rate are also investigated. For different dam heights, seepage behavior is changed and different safety factors are obtained than those of the case of the original design.

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