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Research Article

Performance Evaluation of A High Geomembrane Faced Rockfill Dam In Case of Liner Rupture and Earthquake Risks

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Abstract

This paper presents stability and seepage evaluation of a high rockfill dam with a geomembrane seepage barrier by considering scenarios of a possible occurrence of a large earthquake due to the active faults in the region and also a seepage flow in the dam due to a possible rupture of the geomembrane liner. For this purpose, finite element transient seepage and pseudo static slope stability analyses were both carried out together to assess the critical potential failure surfaces and safety factors of the rockfill slopes. Therefore, pore water pressures on the failure surfaces were first calculated using the time varying (transient) numerical seepage analyses method which is essentially important to determine the time dependent variations of seepage paths and water pressures within the rockfill as well. In the analyses, it was determined that the most critical slope failure case is when a geomembrane liner tears at the time of the highest reservoir water elevation since the hydraulic head is maximum and causes the largest seepage pressure in the rockfill there. Analyses showed that if a strong earthquake struck the region, both the upstream and downstream slopes are safe with sufficiently high safety factors. In addition, in case of a possible tear and leakage on the geomembrane liner, the dam will also withstand well with 2.25 horizontal to 1 vertical slopes. However, it is recommended that constructing a downstream toe drain or a relief well will provide an additional safety measure against any heave occurrence or instability of the rockfill since the embankment and bedrock foundation are pervious causing high seepage pressures at the downstream toe of the dam.

Key words: Rockfill Dam, Geomembrane Liner, Slope Stability, Transient Flow, Seepage Analyses

Ön Yüzü Geomembran Kaplı Yüksek Bir KayaDolgu Barajın Deprem ve Geomembranda Yırtık Olması Durumunda Performansının Değerlendirilmesi

ÖZ

Bu makale sızmaya karşı ön yüzü geomembran ile kaplı yüksek bir kaya dolgu barajın deprem olması veya geomembran kaplamada olası bir yırtık olması nedeniyle baraj gövdesinde sızma oluşması durumlarına karşılık stabilite ve sızma analizlerine dayalı barajın performasını ve güvenliğini değerlendirmektedir. Bu nedenle, sonlu elemanlar zamana bağlı değişen sızma analizi ve şev stabilite analizi baraj gövdesindeki kritik kayma yüzeylerini ve güvenlik değerlerini belirlemek için gerçekleştirilmiştir. İlk olarak baraj gövdesindeki suyun sızma yolları ve kayma yüzeylerine etki eden boşluk suyu basınçları zamanla değişen akım hali için numerik sızma analizleri yapılarak belirlenmiştir. Şev stabilitesi açısından kritik durumun, geoemembrandaki yırtığın rezervuar tamamen dolu

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halde iken nss seviyesinde oluştuğu tespit edilmiştir. Çünkü bu durumda, baraj gövdesinde hidrolik su yüksekliği ve buna bağlı kaya dolguda su sızma basınçları maksimum olmaktadır. Analiz sonuçları göstermiştir ki eğer barajın bulunduğu bölgeye kuvvetli bir deprem etkirse, barajın memba ve mansap şevleri, yüksek güvenlik faktörleri ile kaymaya karşı yeterince güvenli bulunmaktadır. Ayrıca, eğer geomembrane kaplamada bir hasar neticesinde yırtık oluşursa, barajın mansap şevi 2.25 yatay 1 düşey eğimiyle yine yeterince stabil olacağı görülmüştür. Fakat hem kaya dolgu hem de baraj gövdesi altındaki kayaç geçirimli olduğundan, geomembranda bir sızma olursa barajın temelinden sızan suların basıncının sönümlendirilmesi ve güvenle barajın topuğundan uzaklaştırılması amacıyla baraj mansap topuğunda dren veya basınç sönümlendirici bir kuyu tasarlanması tavsiye edilmektedir.

Anahtar kelimeler: Kaya Dolgu Baraj, Geomembrane Kaplama, Şev Stabilitesi, Zamanla Değişen Akım, Sızma Analizi
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1. Introduction

Recently, geomembrane liners have been increasingly used as seepage barriers for embankment dams at sites where sufficient amount of good quality impervious clay material is not available in economical distances. Koerner and Wilkes, [1] stated that 183 earth or rockfill dams incorporating geomembranes are available in the world. Most of those dams are small dams and located on beyond the rich of highly populated areas [2].

Constructed geomembrane lined embankment dams are mostly sandy or gravel fill and their heights are usually low (less than 15 meter) with low reservoir capacities ($H2 \times \sqrt{V} < 200$ wherein H dam height in meter and V is storage volume in million m3 [3]. However, high geomembrane faced earthfill and/or rockfill dams with large reservoir capacities have been rarely constructed on the earth. In addition, design principles of those high embankment dams with geomembrane seepage barriers vary from site to site depending on project characteristics. Since there is always a possibility of defects on the geomembrane liner, engineers usually hesitate using a geomembrane liner as a seepage barrier on high embankment dams with large reservoirs. Since, if a geomembrane liner ruptures, then high seepage forces and internal erosion in the embankment or in its foundation may occur and then slopes of the dam may face with a failure.

Bhowmiki R. et al [4], presented failure analysis of a 8 meter high geomembrane lined reservoir embankment wherein seepage and slope stability analyses were both carried out to detect the causes of failure of the dam. Poulain et al [5], studied also geomembrane lining systems of small reservoirs. Mendoza et al [6], developed some safety factor monograms for small homogeneous embankment dams with low heights and geomembrane liners. In addition to those, Tolooiyana et al [7], analyzed rapid drawdown condition of a channel embankment reinforced by a nonwoven geotextile. Moreover, Briancon et al [8], studied friction at geosynthetic interfaces for different hydraulic conditions and developed equations to calculate friction angle between geotextile and geomembrane.

So, the present paper first of all provides an additional case, a high geomembrane faced rockfill dam where a geomembrane liner was used both to cover the reservoir area and the upstream slope to prevent seepage. This dam is called Yiprak located on pervious bedrock conditions. This study further evaluates safety of the dam if any tear occurs on the geomembrane liner when reservoir water is full. Transient 2-D finite element seepage analyses and slope safety analyses were both carried out together to determine slope safety of the dam for dynamic (earthquake) conditions. Analyses also provided timely variations of seepage pressures and slope safety factors in the dam structure. So, transient seepage analyses showed that the lowest slope safety factors are not always the final seepage stage wherein seepage reaches its steady state. In other words, factor of safety of the slopes may become lowest by time before reaching the final step of the transient analyses.

2. Material and Method

2.1. Design Features of the Dam

Yiprak dam located on 48 km far away Dinar province of Afyonkarahisar city in Turkey is an irrigation purposed high rockfill dam with large reservoir capacity see Fig.1[9]. Storage capacity is 875000 m^3 and maximum height of the dam is 31.5 m. Maximum cross section in the riverbed is also given in Fig.2. Since the bedrock is pervious in the reservoir site and also impervious clay core material is not available in the site, a geomembrane seepage barrier HDPE geomembrane liner overlain with a thin sand bedding layer on the rockfill was used to cover the upstream slope of the rockfill and pervious bedrocks see Fig.1[9].



Fig.1. Google earth view showing Yiprak dam (Google Earth view).[9]

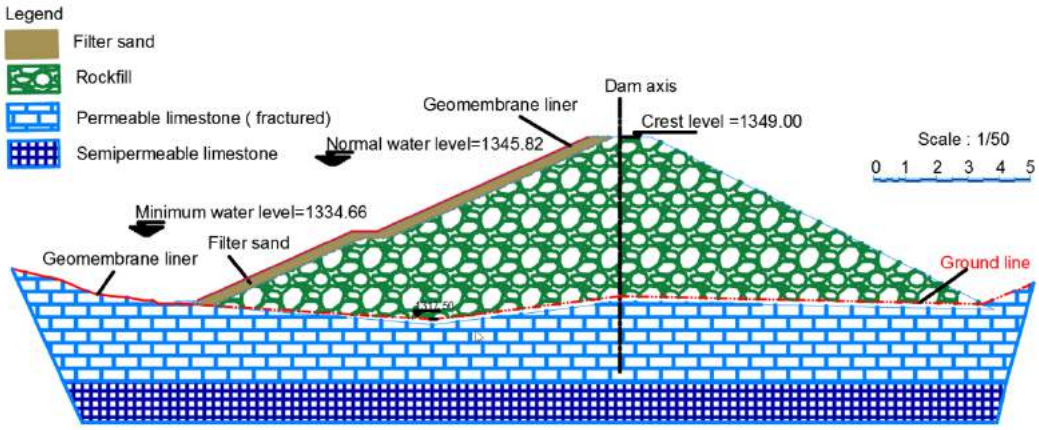


Fig. 2. Maximum dam cross section and bedrock foundation

Structural geology of the dam site is composed of permeable limestone, conglomerate, tuff, consolidated clay and weathered marl with cracks due to tectonic movements. Strata of the rocks are almost horizontal. Mean RQD (rock quality designation) is evaluated as 58. Foundation alluvium beneath the dam is completely excavated. Cohesion and internal friction angle of the bedrock were estimated for the slope stability analyses from the literature by experience and evaluating site conditions such as RQD values, beddings and discontinuity situations etc [10,11]. Permeability of the bedrock was estimated according to the lugeon test results (wherein site lugeon value is mostly larger than 25 indicating the bedrock is highly permeable). Because the bedrock of reservoir and rockfill dam is pervious, both reservoir area and the embankment upstream face were decided to be covered by a geomembrane liner to prevent seepage flow (Fig. 3).

Two active faults close to the Yiprak dam site are available in the region. One is called Tatarlı fault almost 10 km far away the location of the dam. The other is called Dinar fault almost 35 km far away the dam axis (Fig. 4)[12]. The maximum design earthquake (MDE) was selected equal to the Maximum credible earthquake (MCE) which is defined as an upper bound of an expected magnitude (Mw=6,1) for the site. An earthquake of such magnitude could produce 0.21g peak ground acceleration at the dam site calculated by using the attenuation curves produced by Gülkan and Kalkan [13] for Tatarlı fault which is just 10 km far away the dam site.



Fig. 3. A view showing reservoir lining for pervious bedrock

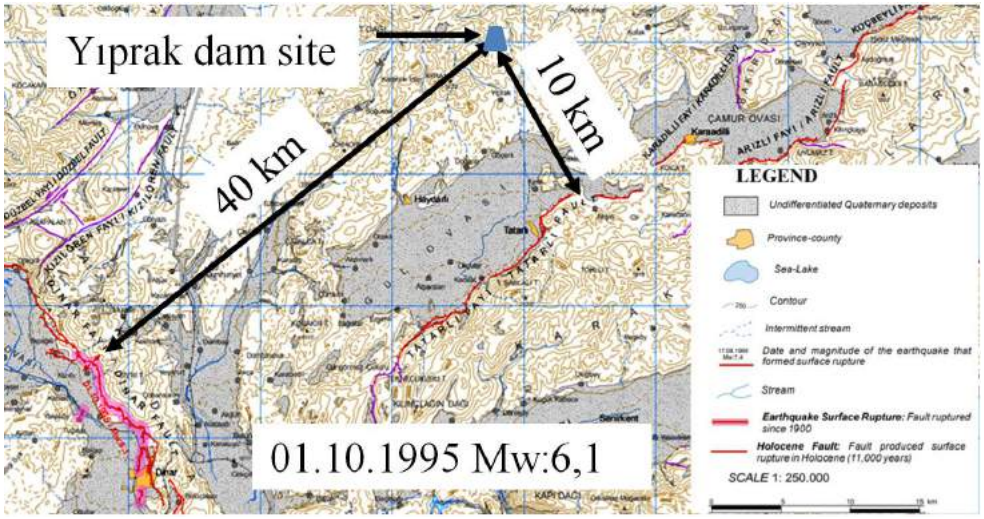


Fig. 4. Active fault map of Yiprak town [12]

3.Results

3.1. Numerical Seepage And Slope Stability Analyses

Defects and tear of geomembrane liners is possible [4]. In case of any tear, there are some available studies in the literature for calculating leakage rates of geomembrane liner systems [14,15,16,17,18,19,20]. Some emprical equations were developed in these studies to determine flow rates based upon laboratory tests for different dimensions of geomembrane defects such as from 2mm to 600 mm.

Weber [21] studied leakage through defects in geomembrane liners under high hydraulic heads. In this study, Weber [21] conducted leakage tests for the geomembrane overlain sand layer and concluded that leakage rates increased with increasing hydraulic heads. In addition, the density of the soil layer beneath the geomembrane affects the leakage rate, and soil layers with low density yield higher leakage rates than soil layers with higher densities, even under low heads. , Weber and Zornberg [22] also numerically analyzed leakage through geomembrane lining systems for dams. However, they only simulated an earth dam rather than a rockfill dam which is presented in this study.

Yiprak dam slopes under geomembrane is 2.25H:1V. Therefore, in order to understand the state of future safety of the predetermined slopes of the Yiprak dam if a tear on the geomembrane liner occurs in different elevations of the reservoir, finite element transient seepage analyses were first performed using software SLIDE [23]. Then, the seepage paths, water pressures in the

embankment and amount of seepage at the downstream toe of the rockfill were calculated. Embankment water pressures due to the rupture of the geomembrane were used in the stability calculations of the slopes of the rockfill dam.

In addition, for the case that the maximum credible earthquake hits the region, existing upstream and downstream slope safety of the dam were also checked for partial (minimum water level) and full storage levels. In this case, bedrock acceleration, MCE of 0.21g was also used as an average horizontal acceleration coefficient for sliding surfaces in limit equilibrium slope stability calculations. The geometry of the section analyzed is seen in Fig. 3. Embankment and bedrock material properties as well as constitutive models used in the analyses are given in Table 2. Yiprak rockfill strength parameters was determined using the relationships developed by [24,25,26]. Since small scale laboratory tests do not always represent well field rockfill properties and conducting large scale rockfill shear tests for each dam project is not practical, shear strength properties of rockfill embankments are usually determined depending on past available data set obtained from different projects, site rockfill construction specifications (such as layer compaction thickness, d_{50} particle size, density, porosity and roughness of the particles). For rockfill, cohesion is zero. However, drained internal friction angle usually varies from 35^0 to 55^0 depending on the confining pressure, particle size (d_{50}), particle breakage, gradation, roughness and porosity of the particles [24,25,26].

Barton and Kjærnsli [25], also developed an Equation (Eqn 2) to calculate drained internal friction angle of rockfill. Permeability value of geomembrane liner was taken 10^{-14} cm/s based on reported values in literature [4].

$$\emptyset' = R\ log\left(\frac{S}{\sigma_n'}\right) + \emptyset_b \tag{2}$$

where R : the porosity, σ_n' : vertical efective total rockfill stres , $\emptyset_b$: basic rockfill friction angle , S: equivalent strength.

Table 2. Yiprak embankment and bedrock material properties.

Material property	Geomembrane	Sandy filter	Rockfill	Bedrock	Sub-bedrock
c (kN/m²)	-	0	0	0	0
∅' (degree)	-	38	40	45	52
γ (kN/m³)	-	19	21	25	25
K (cm/s)	10^{-14}	10^{-3}	10^{-2}	$5x10^{-3}$	10^{-4}

Slope stability analyses were performed using software SLIDE [23]. The factor of safety of the slopes were calculated by widely used Bishop limit equilibrium method described in Eurocode 7 [27] by using Equation 3. Calculated safety factors of upstream and downstream slopes along with transient seepage analyses for all three different scenarios are briefly given in Table 3. Case 1 in Table 3 represents full storage condition along with earthquake effect. Case 2 represents partial (minimum water level) storage with earthquake acceleration. Case 3 is a seepage case due to a tear occurrence of geomembrane liner when reservoir is its maximum level. Figures 5, 6 and 7 corresponds to the Cases 1 and 2. [28]

$$FS = \frac{\sum\left[(c.l + W.tan\emptyset)\left\{cos\alpha + \frac{sin\alpha.tan\emptyset}{FS}\right\}\right]}{\sum W.sin\alpha} \tag{3}$$

where, W: Weight of each slice, l: Length of the failure surface of the slice, $\emptyset$: Internal friction angle of the material, c: Cohesion of the material, α: Angle of the slice with horizontal and FS: Factor of safety.

Table 3. Stability conditions

Cases	Upstream slope safety (FS)	Downstream slope safety (FS)	
1	3.326	1.301	
2	2.207	1.301	
	Time (Days)	**Downstream slope safety (FS)**	**Discharge (m3/day)**
3	200	1.827	0.001025
	500	1.435	240.89
	1000	1.388	240.28
	2500	1.385	242.32

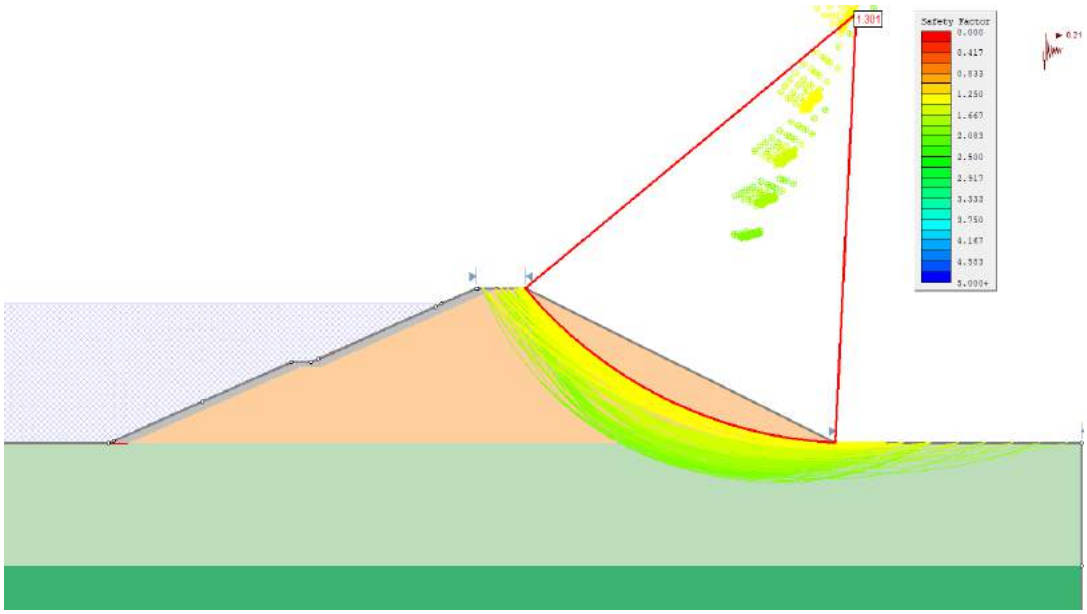


Fig. 5. Downstream slope safety factors of sliding surfaces for full and partial storage cases with 0.21g acceleration coefficient.

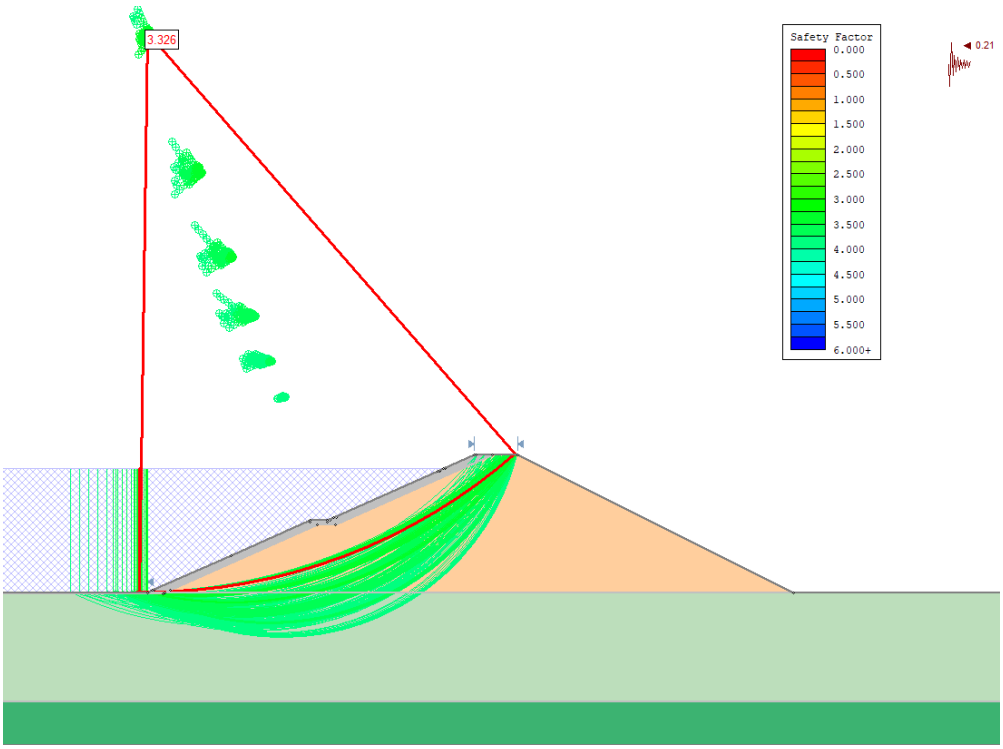


Fig. 6. Upstream slope safety factors of sliding surfaces for full storage case with 0.21g acceleration coefficient.

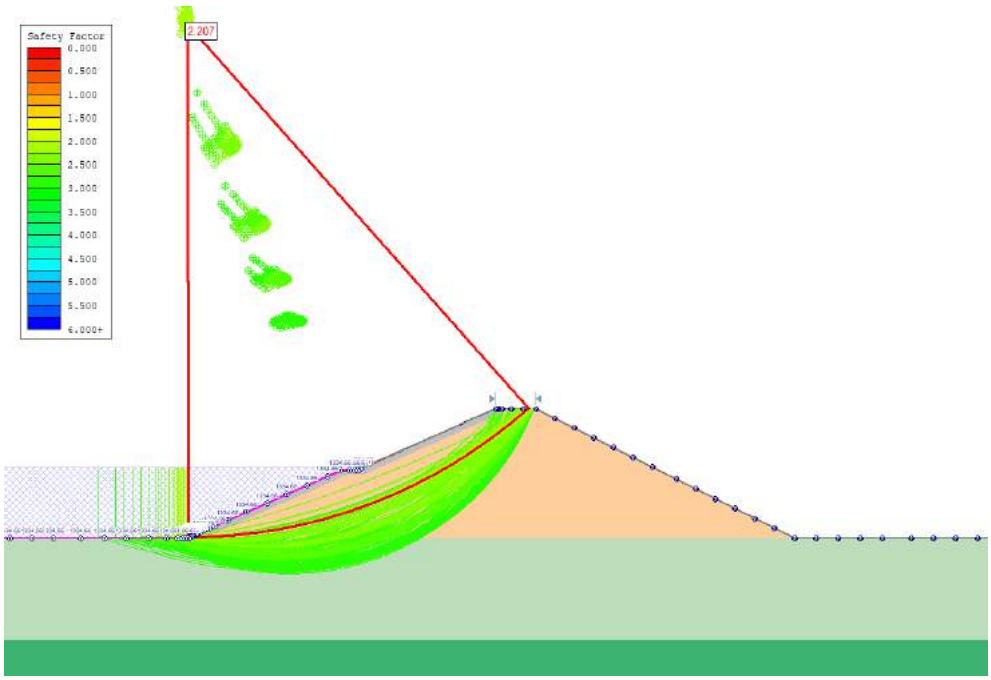


Fig. 7. Upstream slope safety factors of sliding surfaces for partial storage case with 0.21g acceleration coefficient.

In case of leakage in the geoemembrane (Figure 8), numerical transient seepage analyses along with calculated stability safety factors of the downstream slope of the dam are also presented in the following Figures, 9,10, 11 and 12.

As oppose to the downstream slope of the dam, upstream slope will not be a critical slope in terms of any sliding even if seepage occurs due to a rupture on the geomembrane liner since high reservoir water pressure acting on the upstream geomembrane liner has positive impact on the shear strength of the sliding surfaces. Therefore upstream slope safety was not taken into consideration in case of leakages on the geomembrane defects.

As a result of transient numerical seepage analyses, it was observed that factor of safety value of the downstream slope diminishes for each time period (time step) depending on the developed pressures in the pervious rockfill and bedrock. For instance, in general, in the first step as the beginning of the leakage, safety factor of the downstream slope becomes higher. However, due to development of seepage in the rockfill and pervious rock foundation, factor of safety value of the slope decreases and reaches its minimum value at the end of the time step (steady state seepage condition). Numerical seepage analyses were performed using 2-D Laplace seepage equation solved by finite element method (Eqn 4). In the modeling, 3 noded triangle elements were used. The number of the elements was 1500. The number of time stages was 5 with the times, 50, 200, 500, 1000 and 2500 days. The maximum number of the iteration was 100 and tolerance was 0.0001. The general governing equation is for transient seepage flow in a heterogeneous and an isotropic soil [29].

$$\frac{\partial}{\partial x}\left(K_H \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_V \frac{\partial h}{\partial y}\right) + Q' = \frac{\partial \theta}{\partial t'} \tag{4}$$

where, h: total head, K_H and K_V :Hydraulic conductivities in the horizontal and vertical dimensions, Q': applied boundary flux, θ: volumetric water content, t': time.

Since the risk of occurrence of a leakage due to a liner rupture and also a large earthquake at the same time is very low, earthquake effect on the sliding surfaces in slope stability calculations was not taken into account in case of leakage. Seepage analyses provided also amount and pressures of seepage at the downstream toe level of the dam. Numerical transient seepage analyses showed that seepage amount and foundation seepage pressures at the downstream toe of the dam increase by time depending on the development of the leakage from the geomembrane rupture and reach their maximum values at the end of the time step. It was also observed that seeped water in the pervious bedrock caused high seepage pressures at the toe level of the dam. This foundation seepage pressure was the largest one and reached 20 kPa value at the downstream toe of the dam wherein vertical rockfill pressure had also almost same stress value. Therefore, in order to prevent any heave occurrence at the dam toe, it is recommended for this particular dam to construct a downstream toe drain or a relief well.

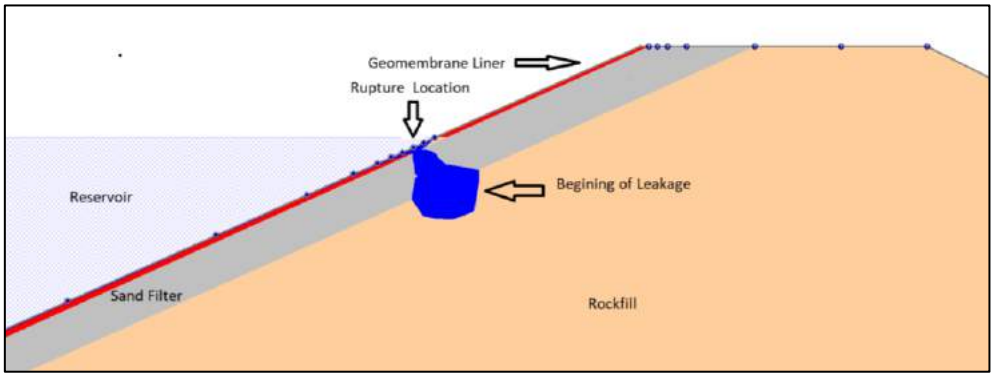


Fig. 8. Rupture location of the geomembrane liner

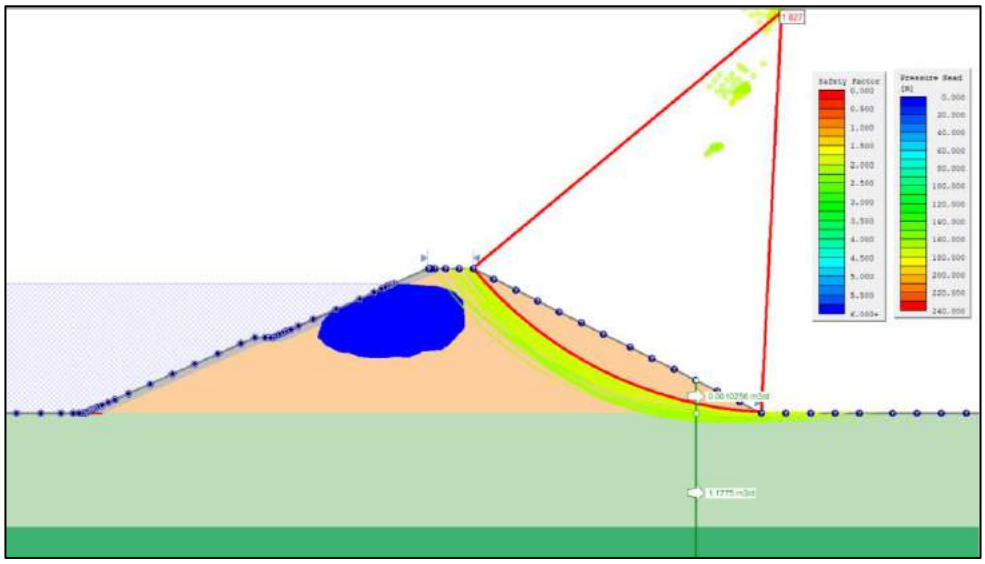


Fig. 9. Flow lines, pressure heads, seepage amount and safety factor of downstream slope in case of a geomembrane rupture when the reservoir is in its maximum level (Starting leakage (time =200 days))

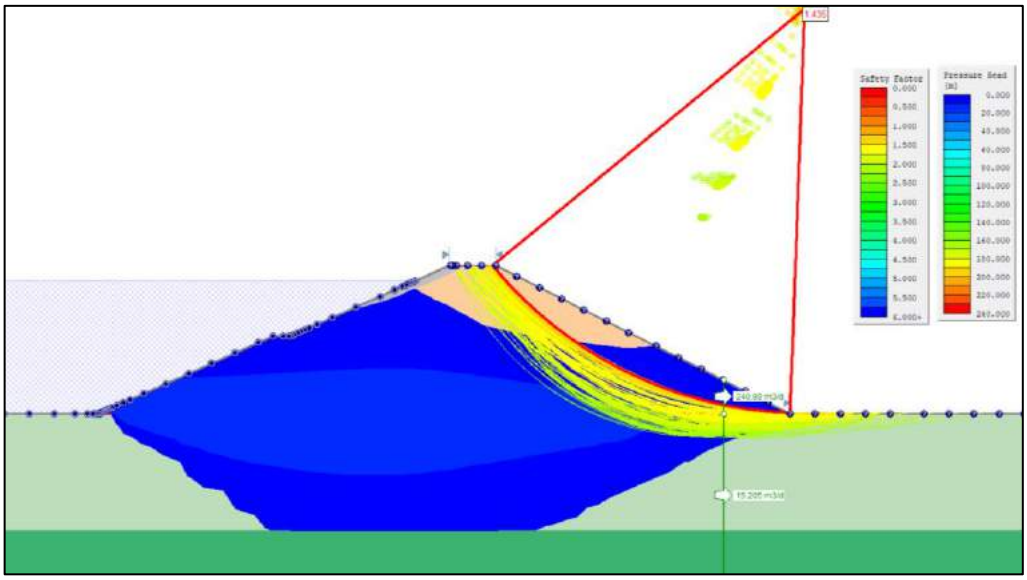


Fig. 10. Flow lines, pressure heads, seepage amount and safety factor of downstream slope in case of a geomembrane rupture when the reservoir is in its maximum level (Starting leakage (time =500 days))

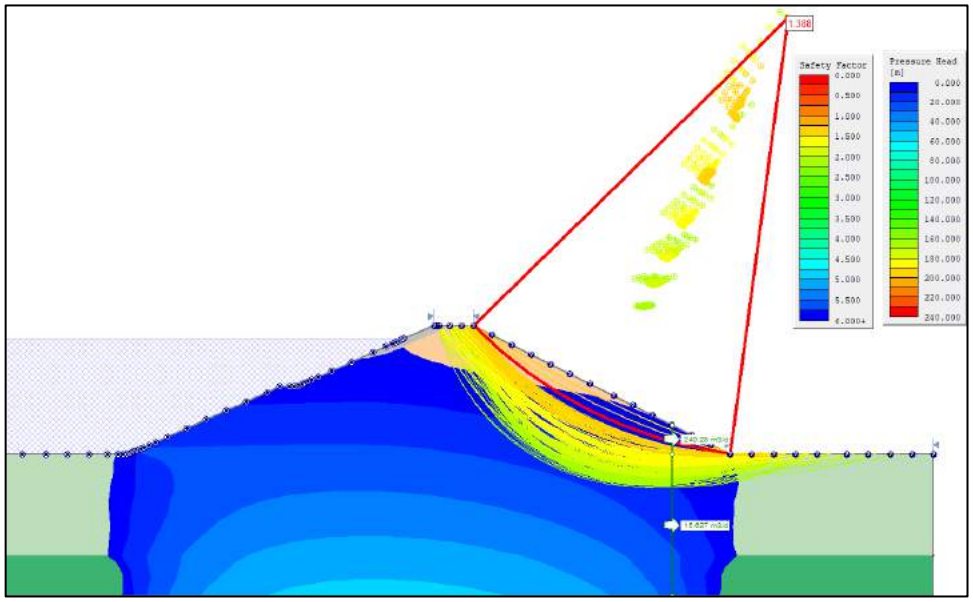


Fig. 11. Flow lines, pressure heads, seepage amount and safety factor of downstream slope in case of a geomembrane rupture when the reservoir is in its maximum level (Starting leakage (time =1000 days))

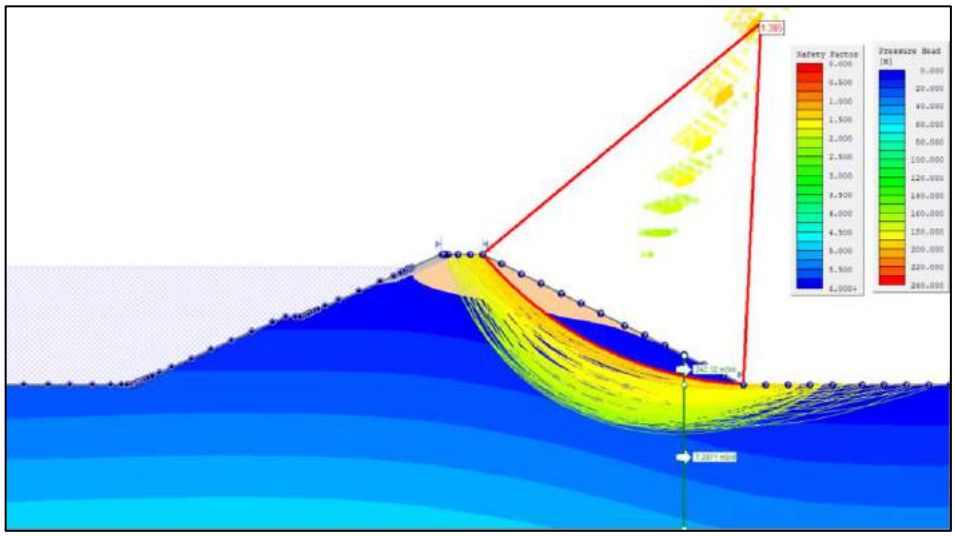


Fig. 12. Flow lines, pressure heads, seepage amount and safety factor of downstream slope in case of a geomembrane rupture when the reservoir is in its maximum level (Starting leakage (time =2500 days - steady state condition))

4. Discussion

In this study, for safety of the Yiprak rockfill dam with geomembrane seepage barrier, findings are explained below:

- Upstream and downstream slopes with 2.25H to 1V are sufficiently stable for full storage and partial storage conditions even in case of a large earthquake causing 0.21g average horizontal acceleration on the sliding surfaces.

- For the upstream slope, the lower sliding safety factors were obtained when the reservoir is at its minimum storage level in case of earthquake with a seismic coefficient of 0.21g. However, sliding safety factors become the highest if the reservoir is its highest level since the highest water pressures acting on the upstream slope face occur. Since then, rockfill strength on the failure surfaces is increased due to the effect of reservoir water pressure.

- Performing transient numerical seepage analyses is quite important to estimate the water pressures for different bedrock or foundation soil conditions as well as to determine the effects on the water pressure and slope safety factor variations. At the beginning of the seepage, it was observed that slope safety factors are usually higher since developed pore water pressures in the rockfill are less. However, at the final stage which is the steady state condition, slope safety factors become the lowest since then seepage pressures are the heighest.

- Even in case of leakages, slopes of the dam will sufficiently be safe.

- In case of a geomembrane liner puncture, It is recommended for this particular dam case that constructing a downstream toe drain or a relief well will provide a safety measure against any heave occurrence or instability of the rockfill toe since the embankment and bedrock foundation are quite pervious causing high seepage pressures.

5. Conclusion

The slopes of Yiprak dam are safely designed. If a rupture occurs on the geomembrane liner when the storage is full, slopes of the dam will still perform well and slopes will be safe against any failure. It is very important to perform transient numerical seepage analyses beside slope safety analyses to understand the development of seepage paths, prediction of pore water pressures and amount of seepage at the downstream part of the dam in case of any tear onthe geomembrane liner. It is also recommended that numerical transient seepage analyses should be performed to assess slope safety of the dam for different embankment types and embankment and foundation material properties.

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