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Research Article

Considerations on the Stability Analyses of Geomembrane Faced Embankment Dams and Slope Optimization - Kızık Dam Case

Uğur Şafak Çavuş

[1]**Civil Engineering Department, Technology Faculty, Suleyman Demirel University, Isparta, Turkey**

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Abstract

It is not so common in dam engineering to design and construct earthfill dams with waterproof geomembrane liners instead of using clay cores. Since any dam failure cause catastrophic results and disasters over large areas located on the downstream side of the dams, dam design engineers generally avoid using geomembrane liners wherein any holes on the liners may cause seepage forces within the embankment materials. Therefore, engineers mostly prefer to use with well known traditional materials such as concrete face, clay fill, and asphalt membrane to provide water tightness for embankment dams. However, in recent years, in the World, there is an attempt to use geomembranes on the upstream faces of embankment dams as water barriers. There are recently some small dams with geomembrane water barriers constructed less than 30 meter heights in Turkey and in the World. In this study, for dam design engineers, it is shown that critical slope loading cases for dam slopes with geomembrane liners are different than those for conventional embankment dams with clay cores. So, this study will provide a technical source and a guide for dam engineers by the way of explaining some important criterions to analyze and design the slope of the geomembrane faced embankment dams along with Kızık dam. In addition this study briefly discusses also some other design principles of geomembrane faced dams. Moreover, the study shows how to optimize the outer slopes of geomembrane faced embankment dams in terms of safety and economy.

Keywords: Geomembrane liners, embankment dams, slope stability, critical loading, optimum slope design

Özet

Baraj mühendisliğinde, dolgu barajların geçirimsizlik perdesini kil çekirdek yerine geomembran malzeme kullanarak sağlamak uygulamada ve tasarımda tercih edilen yaygın bir uygulama değildir. Çünkü bir barajın yıkılması durumunda, barajın mansabındaki geniş alanlar boyunca çok büyük zararlar ve kayıplar meydana gelir. Bundan dolayı baraj mühendisleri barajların su geçirimsizliğini sağlamakta geomembranları kullanmak noktasında geomembranların üzerinde oluşacak bir yırtılma ve delik neticesinde baraj dolgusunda sızma basınçları oluşur diye çekingen davranmaktadırlar. Bu sebeple, mühendisler tasarımlarında daha ziyade geleneksel ama mühendislik davranışları iyi bilinen beton kaplama, kil dolgu veya asfalt membran gibi malzeme ve yöntemleri tercih etmektedirler. Fakat bununla birlikte son yıllarda dünyada barajın su geçirimsizliğini temin etmek için, geomembran kaplı küçük dolgu baraj tasarım ve inşaatları görülmeye başlanmıştır. Türkiye'de ve dünyada 30 yüksekliğin altında bu tür bazı barajlar tasarlanmış ve inşa edilmiş olup bir kısmı da inşaat aşamasındadır. Bu çalışmada, memba şevi geomembran kaplı dolgu barajların şev stabilitesi açısından kritik yükleme şekillerinin klasik kil çekirdekli barajlardan farklı olduğu baraj tasarım mühendisleri için gösterilmiştir. Bu çalışma, baraj mühendisleri için, Kızık barajı şev stabilite analizleri vasıtasıyla, geomembran kaplı dolgu barajların stabilite analizlerindeki önemli kriterleri ve analiz şekillerini anlatan teknik bir kaynak ve rehber hükmünde olacaktır. Ayrıca bu çalışma geomembran kaplı baraj tasarımında dikkat edilmesi gereken diğer önemli hususları da izah etmektedir. Bunlara ilave olarak, geomembran kaplı dolgu barajların şevlerini ekonomik ve teknik açıdan nasıl optimum olarak analiz edileceği sunulmaktadır.

Anahtar kelimeler: Geomembran sentetikler, dolgu barajlar, şev stabilitesi, kritik yükleme, optimum şev tasarımı

1. Introduction

For highly populated regions, any dam failure may cause many deaths and give big damages to the facilities located on the downstream of the dam. Therefore, as a custom, dam designers and contractors usually prefer to work with well-known and experienced materials such as clay cores, concrete, asphalt for water barriers of earth fill/rock fill dams instead of using new types of materials such as geomembranes. However, if there is no clay core material with good engineering properties within an economical distance, then geomembrane faced type of dams may be considered for any earth fill dam design. Kızık Dam was one example of these. Since impervious clay core materials of the dam were located almost 25 km far from the site, Kızık dam

Originally was designed as a geomembrane faced earthfill dam at first. But, later, existing of clay core material source in a reasonably economical distance to the dam site was discovered after a further investigation, geomembrane faced embankment dam design changed to a conventional embankment dam with a central clay core. At the time of the design stage of the geomembrane faced earth fill dam (Kızık dam), many evaluations and discussions were performed among the engineers since a safe design of Kızık dam having a quite large storage volume and 44 m height from foundation level was so important. The dam was also located on highly populated area and on a highly earthquake potential region. The dam was originally designed as a geomembrane faced dam to save from transportation costs of clay core material. However, any irrigation or energy purposed large and high geomembrane faced earth fill dams with high storage capacities (more than 1000000 m^3) comparing to the other dam types are not so common on the earth up to now. According to 2010 ICOLD Bulletin, relatively high number of fill dams with uncovered geomembranes are 47. And, most of the constructed geomembrane faced embankment dams are relatively small and also around 106 with a covered material. So, we can conclude that many geomembrane faced fill dams constructed on the earth are usually either quite small dams or have low storage capacities (generally less than 500000m3). In addition some are also mostly located on the places far from the highly populated regions. Therefore, design of Kızık dam being a geomembrane faced type was left out at final design stage and instead conventional earth fill dam with a clay core was again preferred for the construction by the engineers.

Kızık Dam is located on Sandıklı province of the city of Afyonkarahisar in Turkey. It is now under construction and an irrigation purposed dam. The dam is also located on a region wherein it is mostly probable to have a strong earthquake over 6.0 magnitude. Reservoir volume at the normal water level of the dam is 2070000 m^3. The height of Kızık dam is 37 m from the riverbed and 44 m from the bedrock. Therefore, the alluvium thickness on the dam axis is almost 7 m deep. Spillway structure of the Kızık dam is located on the left abutment. Its discharge capacity is 9.97 m3/s for a 10000 years of return period. Derivation conduit as well as bottom outlet is a 1 m diameter steel pipe and located on the right abutment. Upstream and downstream slopes of Kızık dam were originally designed as 3 horizontal to 1 vertical and 2.5 horizontal to 1 vertical respectively for the geomembrane faced earth fill type as same for the conventional clay core earth fill dam design in the final stage since the engineers hesitated to make stepper slopes for geomembrane faced type of the dam.

In this study critical slope loading cases, loading types, ranges of safety factors, optimum design of outer slopes of geomembrane faced earthfill dams are all discussed and presented along with the Kızık dam which is also under the effect of an earthquake loading. Optimum design of the upstream and downstream slopes are so much important in terms of safety and economy in dam engineering. Since, if outer slopes are designed so gentle, then the volume of the dam and its foundation area increase which also cause larger foundation treatment areas, excavations and refilling with earth fills. Gentle slopes also cause farther and more costly spillway and derivation facilities. Therefore, designing slopes of dams as possible as steep are very important to decrease costs and safety. So, this study, in brief, also provides a good example how to design slopes optimally in terms of the dam's safety and economy. Moreover, some other important design principles of geomembrane faced dams are given.

2. Materials and Methods

2.1. Literature review and evaluation of past studies for embankment dams with geomembrane liners as water barriers of embankments dams

Koerner, R. M. and Wilkes, J. A. (2012) stated that 183 earth or rock fill dams (most of them are small) incorporating geomembranes are available in the world. 45% of those are in Europe, 18% are in USA, 18% are in China and other remaining are scattered in other countries and locations.

Poulain etal (2011) provided a feedback and guidelines for geomembrane lining systems of mountain reservoirs in France

Mendoza et al (2009) developed safety factor monograms for homogeneous earth dams less than ten meters high. In their study, they accepted 1.4 as a minimum safety factor for slopes of an earth fill dam to be sufficiently stable for both the cases of dynamic stability and static stability. However, like in our study, safety factors of dynamic and static stability cases should be different. Since an earthquake loading cause a short time extra loading on any slope sliding surface, required minimum slope dynamic safety factor is usually taken less than minimum static safety factor for a slope to be accepted as safe. In addition, if dynamic threshold slope safety factor is taken as same as the static threshold safety factor, this cause slopes of dams to be flatter and uneconomical. Further, in their study, Mendoza et al did not consider reservoir water pressure as a boundary force on top of the geomembrane. However, this is the real case and has to be certainly considered in the geomembrane faced earth fill dams like in the cases of concrete or asphalt faced dams.

Toloiyana et al (2009) analyzed a channel embankment reinforced by a nonwoven geotextile using two methods: The first method only considered the tensile strength and soil–geotextile interface friction. The second method also considered the drainage function. In both cases, the reinforced embankment was modeled in rapid drawdown condition by the authors

Briancon et al (2002) were discussed outcomes of some experimental modelling of friction at geosynthetic interfaces for different hydraulic conditions to which GLS are exposed, such as rainfall leading to partial or total saturation of the landfill covers on top of the GLS. They also gave some equations to calculate friction angle between geotextile and geomembrane.

2.2. Geology of the site, configuration and material characteristics of the dam

Bedrock on the dam site consists of andesite, agglomerate and tuff. For the Maximum Credible Earthquake on the site, the horizontal earthquake coefficient used for the slope stability analyses of the dam is taken as 0.2g for pseudo static slope stability analyses since the region is in the 1st degree (the most risky) earthquake region in Turkey.

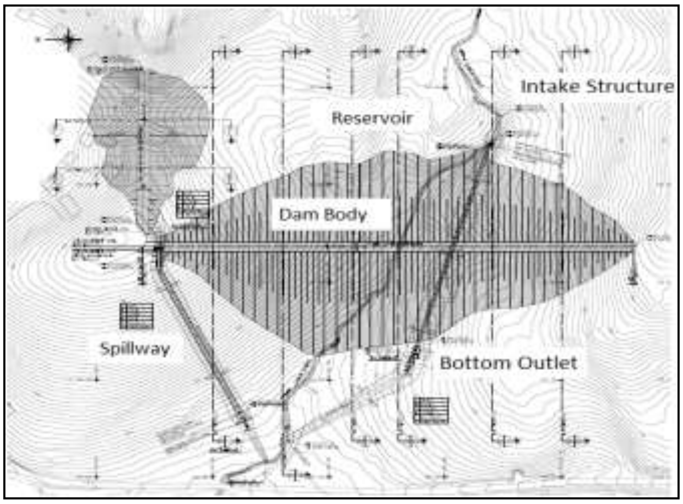


Fig.1. General Layout of Kızık Dam (State Hydraulic Works, 2013)

All possible configurations of the Kızık dam studied carefully at the design stage to find out the safety and least costly dam. It was found that a concrete dam for this irrigation purposed dam would not be feasible. Therefore, dam has to be either rock fill or earth fill type. Since a rockfill dam is generally much more expansive than an earthfill dam, Kızık dam was selected to be an embankment. However, a good clay core material source within a reasonably economical distance at first was not found on the site, then the design was progressed on a sandy fill embankment with a geomembrane faced on the upstream side. This embankment was located on the bedrock after excavating and removing the alluvium completely on the site. The embankment's material, sandy fill behind geomembrane, would be obtained from the sources as much as close to the site. Thus, the general layout of the kızık dam taken into consideration in the first design stage is given in Fig. 1.

Maximum cross section of the dam is also provided in Fig.2. In this stage embankment upstream outer slope with geomembrane face and downstream slope were selected 3 horizontal to 1 vertical and 2.5 horizontal to 1 vertical respectively as same as the slopes chosen in conventional designs. However, since appropriate clay core material was later on finally found in a reasonable distance to the dam axis, the embankment design with a geomembrane faced was left and the design revised to a conventional embankment type with a clay core. However, originally designed upstream and downstream slopes are 3 horizontal to 1 vertical and 2.5 horizontal to 1 vertical respectively remained same for both types of the designs.

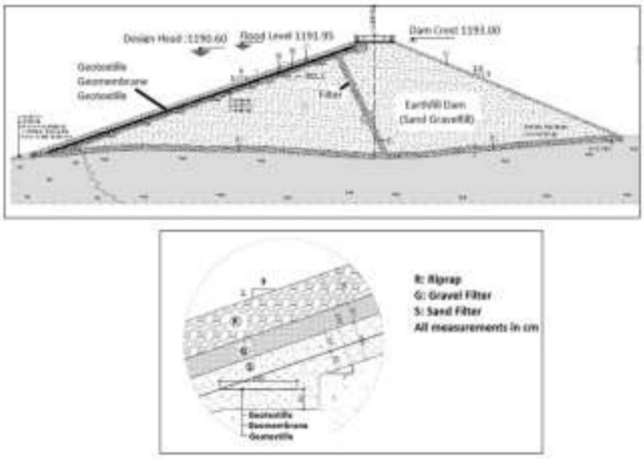


Fig.2. Maximum Cross section and a cross section on the abutment of Kızık Dam in the first alternative of the designs (State hydraulic Works, 2013)

3. Critical Slope Stability Cases for Embankment Dams and Safety Factors

The most critical cases for upstream slopes of conventional embankment dams with a clay core are i) At the end of the construction ii) Sudden drawdown of the reservoirs. However, for downstream slope, the most critical cases are i) At the end of the construction ii) Full of reservoir. On the contrast, for geomembrane faced embankment dams, critical loadings for slope safety differs. In this case, for upstream slope stability analyses, the most critical cases are i)at the end of the construction ii) Full storage and minimum storage level at the end of the irrigation session for irrigation purposed dams. When reservoir is in its highest level (maximum water level) for geomembrane faced embankment dams, reservoir water pressure acts completely on the geomembrane face resulting in increasing of normal soil pressure on the sliding surfaces and as a consequence of it, increasing of shear strength along the sliding surface. Therefore, full storage case is actually not the critical loading for geomembrane faced embankments. Instead, when reservoir water lowered at the end of irrigation or in case of any danger, acting of upstream water pressure on the geomembrane decreases. In such case, shear strength increase on the sliding surfaces due to normal soil stress increase on the sliding surface because of the reservoir water pressure is much less than that of the full storage case. That is why we can accept that minimum reservoir level is much more critical than full storage case for upstream slope of geomembrane faced earth fill/rock fill dams. However, a dam designer has to also analyze full storage loading case for upstream upstream slope design.

For downstream slope stability analysis, critical loadings are as same as those in conventional earth fill/rock fill dams with a clay core wherein those cases are i) At the end of the construction ii) Full of reservoir. A summary of comparison for critical slope failure analyses for both types of embankment dams is given in Table 1.

Table 1. Comparison for critical slope failure analyses for different embankment dams

Earthfill/rockfill dams with clay core		**Earthfill/rockfill dams with geomembrane face**	
UPSTREAM SLOPE	DOWNSTREAM SLOPE	UPSTREAM SLOPE	DOWNSTREAM SLOPE
End of construction	End of construction	End of construction	End of construction
Sudden drawdown	Full storage case	Full storage and minimum storage case after irrigation	Full storage case

As proved in this study, we can say that in terms of slope safety, properly designed well constructed undamaged geomembrane faced earthfill dams may be safer than conventional embankment dams with a clay core. Since, as opposed to the conventional earthfill/rockfill dams with a clay core, in geomembrane faced embankment dams, water pressure acts only on the upstream geomembrane. This means reservoir water does not act within the embankment to cause pore water pressure which decreases shear strength along the sliding surface and also may cause piping or soil erosion due to seepage within the embankment.

Table 2. Minimum required safety factors against slope sliding for earth fill/rock fill dams in Turkey

Upstream slope		**Downstream slope**	
End of construction		End of construction	
Without Earthquake (1.5)	With Earthquake (1.2)	Without Earthquake (1.5)	With Earthquake (1.2)
Sudden drawndown or min reservoir level		Full storage case	
Without Earthquake (1.0)	With Earthquake (1.0)	Without Earthquake (1.5)	With Earthquake (1.2)

In Turkey, when a pseudo static earthquake slope stability analysis is done, the minimum accepted safety factors for upstream embankment slopes are 1.2 for the end of construction case and 1.0 for the drawdown case. Minimum acceptable safety factors for downstream embankment slopes are, however, 1.2 for both the end of construction and full of reservoir cases (Table 2).

4. Slope Stability Analyses of the Kızık Dam with an Upstream Geomembrane Face

In the design stage of the geomembrane faced Kızık dam, slopes were selected 3 horizontal to 1 vertical for the upstream slope and 2. 5 horizontal to 1 vertical for the downstream slope as same as those normally selected for the conventional earthfill dams with a central clay core. However, as proved and discussed in this paper, it is possible to make steeper slopes and then as a consequence it is possible to make the cost of the dam less and save Money. Since, if we design sufficiently safe steeper slopes, then embankment volume and foundation treatment beneath the embankment decrease. In addition due to steeper slopes, upstream and downstream embankment lay out on the river bed and abutments do not spread to larger areas. This also cause some decrease in the length of bottom outlet and spillway structures. All these result in cost savings.

Therefore sufficiently safe and economical slope design for geomembrane faced embankment dams have to be sought in all designs instead of designing slopes conventionally. Steeper slope design is more possible for geomembrane faced earth fill dams than that for conventional embankment dams with a clay core since there is no water normally within the embankment due to prevention of seepage of reservoir water into the embankment by the impervious geomembrane barrier.

4.1. Pre-evaluations before running slope stability analyses

Possible slopes to be chosen for the design are 3H/1V, 2.5H/1V or 2H/1V for the upstream slope and 2.5H/1V or 2H/1V for the downstream slope. Steeper upstream slope than the 2H/1V is not considered for sandy gravel earth fill material due to the risk of the segregation and construction difficulties of the geomembrane placement. For the upstream slope we decided the most critical slope loading cases for the stability as:

- Earthquake effect at the end of construction and
- Earthquake effect when the reservoir is full with water

Since, the dam is an irrigation dam, then only five months of irrigation season, reservoir water will get gradually and partly lower levels and finally it will reach the minimum level only at the end of the irrigation session for a short period of time. Therefore, the risk of the having a maximum design earthquake considered for the region just when the water level is in its lowest time is quite low. So, most of the year dam will have high storage levels causing high pressures on the geomembrane face and a high seepage risk if any damage occurs on the geomembrane barrier. Thus we concluded that the full storage case with an earthquake coefficient to run a pseudo static slope stability analyses is much more critical than the case of the storage with a minimum reservoir level.

When full storage case considered dynamic reservoir water pressure acting on the geomembrane barrier due to earthquake should also be taken in the analysis for example by using westergard calculation. However, this dynamic water pressure causes additional pressure to the static water pressure and as a consequence it also causes strength increase along the sliding surfaces. Therefore, in our cases we did not considered dynamic reservoir water pressures to stay on safer side. Minimum acceptable safety factors are 1.5 for static case and 1.2 for earthquake case. Ice effect on the upstream slope is also not considered for the upstream slope stability analyses since the region is although located on a cold region. Freezing of the reservoir water is not so common. However, it should be marked that for very cold regions, freezing of reservoir water may damage geomembrane if not protected well and also cause additional horizontal load on the upstream face the dam. Embankment material properties used in slope stability analyses in this study are also given in Table 3.

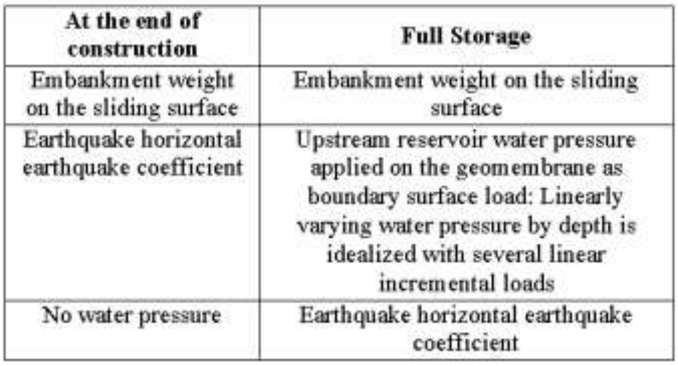
Table 3. Material properties of the Kızık Embankment

	γ_{moist} (kN/m^3)	γ_{sat} (kN/m^3)	c_{dry} (kN/m^2)	c_{sat} (kN/m^2)	ϕ	r_u
sandyfill	16.5	17.6	0	0	38	0

5. Pseudo Static Slope Analyses and Optimum Design of Outer Slopes of Kızık Dam

To determine the design safety factors of the upstream and downstream slopes of the Kızık dam for the maximum horizontal seismic acceleration coefficient of 0.2g obtained for the maximum credible earthquake with a magnitude of 6.5 for the region, we run slope stability analyses using the WinStabl program, adapted to windows platform by Peter J. Bosscher, from the original Purdue University STABL code developed by Ronald A. Siegel (1975). This program analyses slopes by one of the limit equilibrium methods such as Swedish circle, modified Bishop and Janbu. In all of our analyses we preferred modified Bishop method for calculating factor of safeties of the sliding surfaces. Sliding surfaces are selected as circles. If an embankment is consist of homogeneous earthfill material then any slope sliding is most probably either circular or near circular. In all analyses we used 100 trial surfaces to obtain the most critical one with the lowest factor of safety. At the outcome of the analyses, ten most critical sliding surfaces among hundred tried surfaces are obtained as seen on the figures 3,4,5,6 and 7 with lowest factor of safeties. The first one with the lowest factor of safety indicates that this sliding surface is the most critical one. Loading types for the critical cases are also summarized in Table 4 below:

Table 4. Loadings for different cases



At the end of construction	Full Storage
Embankment weight on the sliding surface	Embankment weight on the sliding surface
Earthquake horizontal earthquake coefficient	Upstream reservoir water pressure applied on the geomembrane as boundary surface load: Linearly varying water pressure by depth is idealized with several linear incremental loads
No water pressure	Earthquake horizontal earthquake coefficient

5.1. Upstream slope optimization

As opposed to the customized design we first started slope analyses with a 2.5 horizontal/1 vertical upstream slope to check whether the slope is sufficiently safe instead of analyzing the slope 3 horizontal to 1 vertical upstream slope which was chosen in the original design. Then, we obtained that calculated safety factors for the end of construction and full storage cases of the upstream slope are 1.39 and 1.58 respectively (Fig. 3 and 4) which are much higher than the required minimum value of 1.2 in case of earthquake effect.

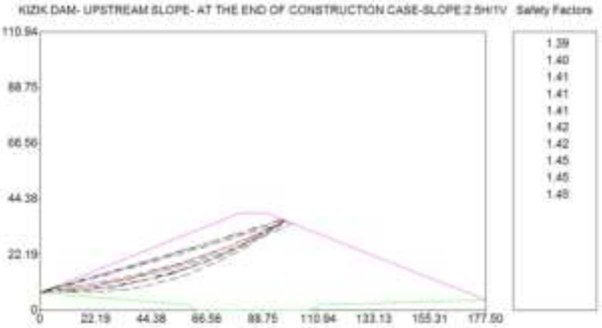


Fig. 3. Ten most critical sliding surfaces and minimum safety factors of Upstream slope of the Dam: Slope is 2.5H/1 V for the end of construction case with 0.2g earthquake coefficient

As seen on the figures, safety factors for the 2,5H/1V slope for full storage case with the earthquake coefficient of 0.2g are quite high (almost 1.6) comparing to the safety factors of the end of construction case. In both cases, calculated lowest factor of safeties for critical sliding surfaces are still much higher than the required Turkish criteria wherein factor of safety of the dam slopes has to be higher than 1.2 for earthquake cases. The reason for increasing of safety factors when reservoir water is full that the water pressure acts directly on the upstream of the geomembrane which positively increases the shear strength of the failure surfaces.

Thus, it is concluded that the upstream slope of the dam with 3H:1V is over conservatively and uneconomically designed which means that the slope is so gentle. Even 2.5 horizontal to 1 vertical slope is found quite safe for both loading cases. So, it is concluded that the upstream slope of the dam was designed conservatively and costly. This showed us how important to find an optimum solution for the upstream slope design of the Kızık dam.

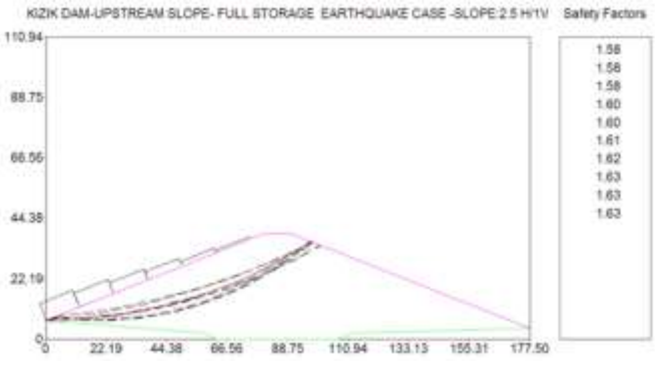


Fig.4. Ten most critical sliding surfaces and minimum safety factors of Upstream slope of the Dam: Slope is 2.5H/1 V for the full storage case with 0.2g earthquake coefficient

Then the upstream slope is taken as 2 horizontal to 1 vertical to seek further whether more economical solution is possible along with safety. In this case, minimum calculated safety factors for ten most critical sliding surfaces are around 1.0 (Fig.5) for an earthquake coefficient of 0.2g which is lower than the required 1.2 meaning slope is not so safe in this situation and the slope is almost limit equilibrium state with values of 1.0.

However, a designer may still consider that this slope may be accepted as safe since there will be no reservoir water at the end of construction to danger livings downstream in case of any slope failure. In addition, Kızık dam will also never completely become empty during operation after the reservoir was filled. So, when it has a full reservoir 2H/1V upstream slope becomes quite safe even in case of the earthquake effect with a minimum safety factors around 1.3 (see Fig. 6). The reason for increasing of safety factors in full reservoir case is due to the water pressure acting directly on the upstream of the geomembrane which increases the shear strength of the failure surfaces. Since, the dam is an irrigation dam, then only five months of irrigation season, reservoir water level decreases gradually and partly until the minimum water level. So, most of the year dam will have full storage and the other times will operate with partial upstream water pressure. Partial water pressure even causes some increase in the slope safety factor values in some degree. In addition, the risk of an earthquake strike to the dam along with five months of irrigation and to the time in which the reservoir water is at the lowest level is quite low.

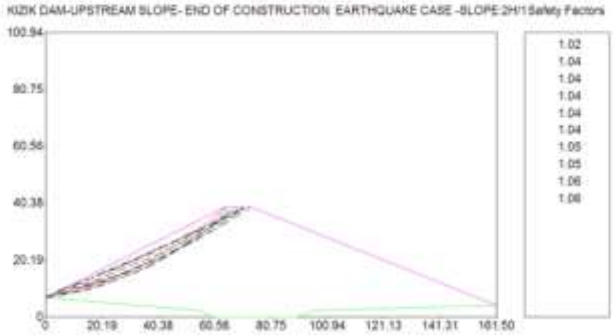


Fig.5 Ten most critical sliding surfaces and minimum safety factors of Upstream slope of the Dam: Slope is 2H/1 V for the end of construction case with 0.2g earthquake coefficient

Thus, we can conclude that even 2H/1V upstream slope is sufficiently safe and can be chosen for the design as well since in this case, bottom outlet structure length and embankment volume considerably decrease which cause the dam to be much more economical.

However, if a designer wants to stay on safer side, then it is recommended that he/she should prefer 2,5H/1V slope which will be sufficiently safe and less costly comparing to the original design with 3H/1V slopes.

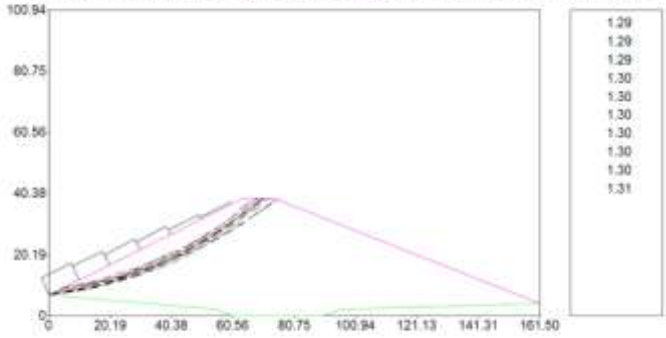


Fig.6. Ten most critical sliding surfaces and minimum safety factors of Upstream slope of the Dam: Slope is 2.5H/1 V for the full storage case with 0.2g earthquake coefficient

5.2. Downstream slope optimization

The most critical loadings for the downstream slope are at the end of construction and full storage cases. However, strength properties will be same and pore water pressure will be zero within the embankment for both cases resulting in same factor of safeties in the slope stability analyses. Since, there is no seeping water affecting downstream slope stability for geomembrane faced dams due to geomembrane water barrier on the upstream face of the dam, and dam is also always in dry state if geomembrane is not damaged, material. So, calculated minimum safeties for ten most critical sliding surfaces of downstream slope of Kızık dam for end of construction and also full reservoir cases are found a little higher than 1.2 (Fig. 7) indicating that downstream slope is designed sufficiently safe and economical. So, no need to make a steeper downstream slope.

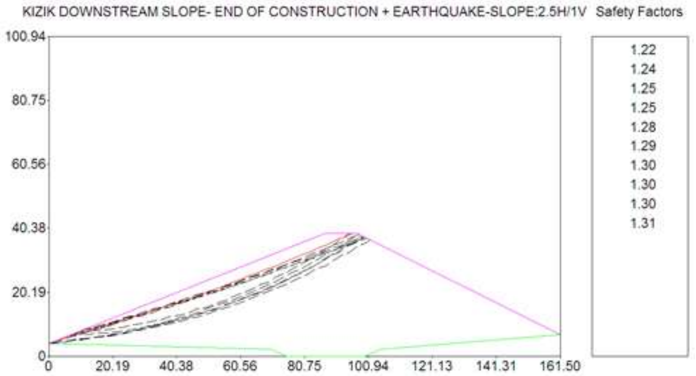


Fig.7. Ten most critical sliding surfaces and minimum safety factors of Downstream slope of the Dam: Slope is 2.5H/1 V for the end of construction and full storage cases with 0.2g earthquake coefficient

6. Other Considerations, Fundamental Design and Construction Principles for Large Geomembrane Faced Embankment Dams

Beside other dam types, geomembrane faced dams should only be considered to construct under those circumstances:

i) Reservoir volume < 1000000 m3,

ii) If there is no available good quality and/or sufficient amount of clay core within economical distances

iii) If it is not possible to construct other conventional well known dam types such as concrete faced or asphalt faced embankments.
However, it may also be possible to design and construct medium high geomembrane faced embankment dams with quite large reservoir volumes. However in this case important care have to be given for the design and construction since any damage of the geomembrane face may result in seepage erosion within the embankment and a complete failure of the dam. So, if a designer decides to construct an embankment dam with geomembrane barrier instead of impervious clay core, then the designer has to give special care to those:

iv) Geomembrane should be located on the upstream face of the dam instead of locating it within the embankment as a central impervious core. Since a geomembrane liner on the upstream slope of the dam resist whole reservoir water pressure from the upstream side of the dam which increases normal forces applied on the sliding surfaces and also increases the shear resistance along the sliding surfaces. On the contrast, if geomembrane liner is located within the embankment as a water barrier, then the earth fill becomes saturated at upstream side of the membrane and dry at the downstream of the membrane barrier wherein some differential settlements and damages to the geomembrane barrier may occur.

v) Geomembrane has to be protected by geotextiles both ion top and bottom of the liner

vi) Placement of the geomembrane at the valley abutments have to be carefully done not to cause any seepage of the reservoir water.

vii) If the rock foundation is pervious and needs to make grouting, then toe slabs at the abutments have to be provided and geomembrane liner is extended the toe slabs and tightly fixed there.

viii) Grouting has to be performed from the top of concrete toe slabs.

ix) For cold regions, to prevent any ice force and disturbances on the geomembrane, it should be protected with some earth fill materials like a sandy- clay fill on the upstream side,

7. Evaluations and Conclusions

For slope design of the geomembrane faced earth fill/rock fill dams, some guidelines are summarized below:

- ✓ For upstream slope stability analyses, the most critical cases are i)at the end of the construction ii) Full storage and minimum storage level at the end of the irrigation session for irrigation purposed dams.

- ✓ For downstream slope stability analysis, critical loadings are as same as those in conventional earth fill/rock fill dams with a clay core wherein those cases are i) At the end of the construction ii) Full of reservoir.

- ✓ For full storage case, dynamic reservoir water pressure acting on the geomembrane barrier due to an earthquake should not be taken into consideration in limit equilibrium slope stability analyses to stay on the safer side. Since this dynamic water pressure causes additional pressure to the static water pressure and then cause strength increase along the sliding surfaces.

In conclusion, in this study, safety of the outer slopes of the conventional type earth fill dam, Kızık Dam is first checked by running circular type slope stability analyses. Then, optimum slopes are also determined in terms of safety and economy. The downstream slope is found sufficiently safe and economical. Therefore, it is not changed. However, since upstream slope is designed conservatively, this slope is designed steeper with a 2.5H:1V slope. So, upstream slope become more economical. Thus, the other dam facilities such as spillway and derivation structures also become much more economical since their lengths is possible to be less.

Finally, we can concluded that well-constructed undamaged geomembrane faced earth fill dams may be safer than conventional embankment dams with a clay core. Since, as opposed to the conventional earth fill/rock fill dams with a clay core, in geomembrane faced embankment dams, water pressure acts only on the upstream geomembrane. This means reservoir water does not act within the embankment to cause pore water pressure which decreases shear strength along the sliding surface and also may cause piping or soil erosion due to seepage within the embankment.

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