



Research Article / Araştırma Makalesi
**EVALUATION OF SLIDING STABILITY IN CONCRETE GRAVITY DAMS
USING MULTIPLE WEDGE ANALYSIS**

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ABSTRACT

The concrete gravity dams are huge structures storing a large amount of water. For this reason, they cause especially irreparable loss of lives during the earthquake. The stability of a structure is associated with safety level of the structure. The stability of a concrete gravity dam is in accordance with evaluation of safety factor against sliding with using equivalent static loadings acting friction model of dam-soil interaction zone and dynamic effects of earthquake on the dam. In this study, the sliding stability of concrete gravity dams is evaluated with Multiple Wedge Analysis method based on Mohr-Coulomb Failure Criterion. Sanyar concrete gravity dam is chosen as a numerical application. For usual and unusual loading conditions, the effects of the parameters which are dam base angle, cohesion and internal friction angle of soil, uplift pressure and earthquake loads on the sliding stability of the dam are investigated. The changing of safety factors obtained according to the analysis is evaluated and the parameters acted on sliding stability of the dam are determined. After the analysis, it is shown once again that acceleration of earthquake has the most important effect which can hazard the sliding stability for dams. Cohesion and internal frictional angle of the soil interacting with the structure are other two important parameters which determine sliding stability. It is shown once again that uplift pressure has a detractive effect on sliding stability. In addition, it is established that the changing of dam base angle affects sliding stability.

Keywords: Concrete gravity dam, factor of safety, multiple wedge analysis, sliding stability.

ÇOKLU PARÇA ANALİZ YAKLAŞIMIYLA BETON AĞIRLIK BARAJLARIN KAYMA STABİLİTESİNİN DEĞERLENDİRİLMESİ

ÖZ

Beton ağırlık barajlar, çok miktarda su depolayan önemli yapılardır. Bu sebeple, özellikle deprem esnasında yıkılmaları buldukları çevre için telafisi mümkün olmayan can kayıplarına yol açabilir. Bir yapının stabilitesi, yapının güvenlik seviyesi ile ilişkilidir. Bir beton ağırlık barajın stabilitesi ise, baraj-zemin birleşim bölgesinin sürtünme modeli ile baraj üzerindeki depremin dinamik etkilerini temsil eden yükleri kullanarak kaymaya karşı bir güvenlik katsayısının hesabıyla bağlantılıdır. Bu çalışmada, Mohr-Coulomb kırılma teorisini esas alan Çoklu Parça Analiz (ÇPA) yaklaşımıyla beton ağırlık barajların kayma stabilitesi değerlendirilmiştir. Sayısal uygulama olarak Sanyar beton ağırlık barajı seçilmiştir. Baraj taban açısı, zeminin kohezyon ve içsel sürtünme açısı, taban kaldırma kuvveti ve deprem ivmesi parametrelerinin barajın kayma stabilitesi üzerindeki etkisi incelenmiştir. Baraj tabanında yeterli drenajın yapılmadığı kabulüyle taban basıncı hesaplara katılarak analizler yapılmıştır. Elde edilen güvenlik katsayılarının yapılan analizlere göre değişimi değerlendirilerek, barajın kayma stabilitesinde etkili olan parametreler belirlenmeye çalışılmıştır. Yapılan analizler sonucunda, deprem ivmesinin, barajların kayma güvenliği riskli hale getirecek en önemli parametre olduğu, barajın etkileşim içinde olduğu zeminin içsel sürtünme açısı ile kohezyon değerlerinin kayma güvenliğini belirleyen önemli iki parametre olduğu, taban basıncı değerinin kayma güvenliği üzerinde azaltıcı bir etkiye sahip olduğu bir kez daha görülmüştür. Ayrıca baraj taban açısının değişiminin kayma güvenliğini etkilediği belirlenmiştir.

Anahtar Sözcükler: Beton ağırlık baraj, çoklu parça analizi, güvenlik katsayısı, kayma stabilitesi.

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1. INTRODUCTION

In accordance with the seismic zones map of Turkey, %92 of country is in earthquake region, %95 of population is living under earthquake risk and also %98 of great industrial centers and %93 of dams are in earthquake region. [1]. Distribution of concrete gravity dams in accordance with the seismic zones are given in Figure 1. In general examination of the behavior of these dams built to generate power under dynamic loads has an important place in engineering studies. Structural stability is directly related with factor of safety chosen for analysis. Stability of a concrete gravity dam is related with dynamic effects that representing the loads in which are used for determining the factor of factor for sliding [2]. There are lots of studies conducted about sliding stability of the concrete gravity dams. El-Aidi [3], studied on non-linear behavior of Pine Flat Dam by using finite element analysis method for water and dam, examined the openings and crack propagation by the help of resistance coefficients independent from frequency for base rock and determined permanent displacements. Leger and Katsouli [4] are researched for sliding stability of the concrete gravity dams by using finite element method for dam, water and foundation. This study had shown that non-linear behavior of the interface of dam-base rock is decreased the seismic behavior of the dam. Chopra and Zhang [5] are researched sliding motion of the concrete gravity dam that placed on rigid base layer on a simple model and determined that base sliding is more important than dam vibration. Zegarra [6] determined that concrete dam had produced sliding for hydrodynamic pressure together with non-linear base movement analysis based upon sliding, sliding motion has energy absorption on the dams that established on rigid base and sliding motion is occurred during strong ground motions but system is remained stabilized. Chavez and Fenves [7] are researched non-linear sliding motion effect of the earthquake behavior on interface dam-base rock and proved that sliding displacement is sensitive to base cohesion. Fenves and Chavez [8] studied on a model for dynamic analysis that includes concrete gravity dam sliding. They have revealed the coefficients affecting sliding displacements and shown the relationship between sliding displacement and factor of safety. Mir and Taylor [9] are researched dynamically induced the sliding and overturning behaviors of a typical low height dam that has one monolith crack at base. They declared that seismic sliding motion can be estimated by creating a contact surface algorithm on finite element analysis in accordance with the results of experimental and analytical studies. Seismic induced sliding can be estimated using Newmark sliding block. Martt et. al [10] researched for situations that caused the collapse of Austin concrete gravity dam that constructed in one of the east states of the USA, Pennsylvania in 1909. They revealed that seepage cannot be prevented and collapse is happened due to sliding along sandstone-shale interface.

In this study, sliding stability of a concrete gravity dam is researched by Multiple Wedge Analysis based on Mohr-Coulomb Failure Criterion. For numerical application, Sarıyar concrete gravity dam is chosen. For usual and unusual loading conditions; parameter effects of base angle of the dam, cohesion and internal friction angle of the soil, uplift pressure and earthquake load on the dam sliding stability are researched. Analyses are performed by accepting the adequate drainage and not being the base pressure. Determined factor of safety is evaluated for changes in analysis and parameters that are effective in sliding stability of concrete gravity dams are tried to be identified.

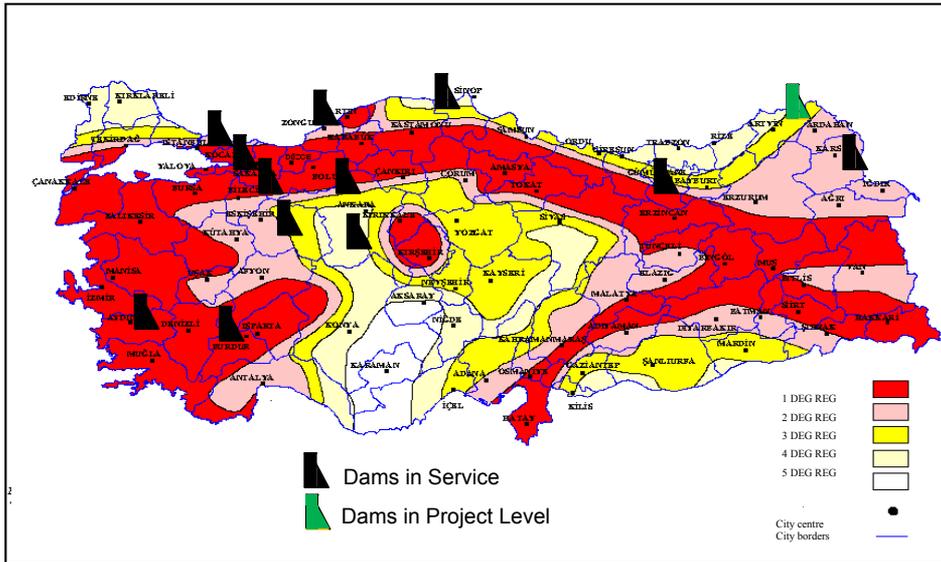


Figure 1. Seismic zones map in Turkey and layout of concrete dams

2. FORCES ACTING ON CONCRETE GRAVITY DAMS

Concrete gravity dams that are carrying the loads acting on themselves with their gravity and they are exposed to lots of forces during their service duration. Forces acting on dams within this period and their resultant forces are shown in Figure 2.

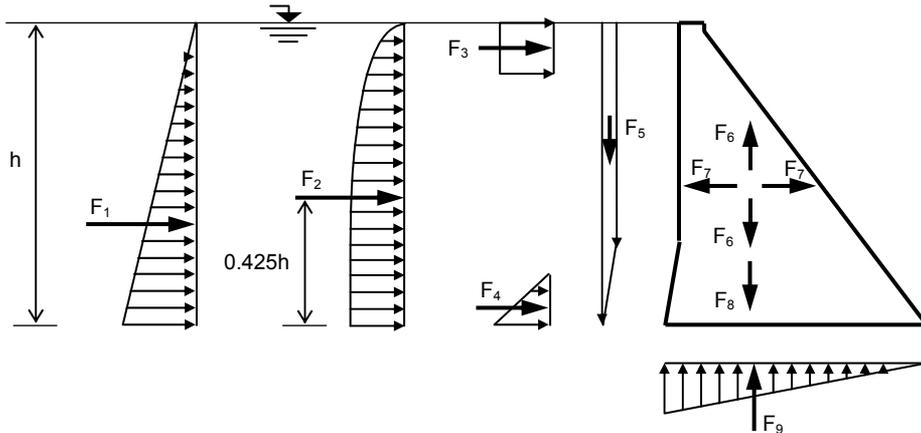


Figure 2. Forces acting on concrete gravity dams and their resultant forces

Force F_1 is hydrostatic water force acting on the dam.

Force F_2 represents the hydrodynamic pressure forces that are created in reservoir due to ground motion. This force is calculated with the following formula:

$$F_2 = (0.555a\gamma_w h^2) \tag{1}$$

Here a , γ_w and h are acceleration of the earthquake, unit weight of water, depth of water behind the dam, respectively. Application point of this force to dam body is $0.425h$ point from above the base [11].

Force F_3 is pressure force that caused by the temperature changes during expansion and shrinkage of ice developed on the reservoir in cold climates. Ice pressure value generally changes between $320\text{-}1600 \text{ kN/m}^2$ [11].

Force F_4 represents the silt pressure occurred in deep of the dam due to silt development. This pressure value is calculated with Rankine theory by using submerged weight of the silt.

Force F_5 is weight of water caused by dam upstream face geometry.

Force F_6 and F_7 are forces developed due to vertical and horizontal acceleration of the earthquake. These forces are determined by multiplying of earthquake acceleration developed in related directions and dam mass.

Force F_8 is force that caused by weight of the dam and application point is on the center of gravity of the dam.

Force F_9 represents the uplift force caused by the seepage of water due to faults in base and imperfections in concrete mass at dam base.

3. FACTORS OF SAFETY OF CONCRETE GRAVITY DAMS FOR VARIOUS LOADING CONDITIONS

Loading conditions during service life of a structure can be classified as usual, unusual and extreme. Usual loading condition is the expected loading during service life of the structure continuously. In this loading case, structure is expected to have elastic behavior. Unusual loading refer to operating loads and loading conditions that are of infrequent occurrence. Structure is accepted to have non-linear behavior. Extreme loading is defined as loading condition that characterized by impossible infeasible conditions and emergency conditions. Factors of safety of these loading conditions are shown in Table 1.

Table 1. FS (Factors of Safety) values for Concrete Gravity Dams [12]

Site Information Category	Loading Conditions		
	Usual	Unusual	Extreme
Well Defined	1,40	1,20	1,10
Ordinary	1,50	1,30	1,10
Limited	3,00	2,60	2,20

4. MULTIPLE WEDGE ANALYSIS

In this method gravity dam body and soil acting on the dam are assumed to act as a wedges system and the system is created by combination of separate wedges [2,12]. Resultant forces that are acting on these wedges and interaction of every wedge that are creating multiple wedge system together with adjacent wedges are shown in Figure 3.

As it can be seen in Figure 3, dam-soil system can be separated into structural wedge, driving and resisting wedges according to soil stratification. By this way, equilibrium equations can be handled for every wedge as parallel and perpendicular to the sliding surface. N_i and T_i forces will become at the following;

$$\begin{aligned} \sum F_n = 0 \Rightarrow N_i &= (W_i + V_i) \cos \alpha_i - U_i \\ &+ (H_{Li} - H_{Ri}) \sin \alpha_i \\ &+ (P_{i-1} - P_i) \sin \alpha_i \end{aligned} \quad (2)$$

$$\begin{aligned} \sum F_t = 0 \Rightarrow T_i &= (H_{Li} - H_{Ri}) \cos \alpha_i \\ &- (W_i + V_i) \sin \alpha_i \\ &+ (P_{i-1} - P_i) \cos \alpha_i \end{aligned} \quad (3)$$

Here,

$(P_{i-1} - P_i)$ is representing the total force acting on part as horizontally in wedge

W_i is representing total weight of water, base, rock or concrete in wedge

V_i is representing the vertical force that applied on the upper part of the wedge

U_i is representing the uplift force that acting on the wedge at sliding plane

α_i is representing angle between sliding plane of the wedge and horizontal

H_{Li} is representing any horizontal force applied on wedge above top or below bottom of left side adjacent wedge

H_{Ri} is representing any force applied on wedge above top or below bottom of right side adjacent wedge

L_i is representing length of wedge along slip plane

For this method based on Mohr-Coulomb Failure Criterion, there is sliding factor of safety determined to carry the sliding mass that created from resisted wedges and driving wedges in dam body along sliding surfaces. In accordance with the Mohr-Coulomb Failure Criterion sliding resistance components can be written at the following:

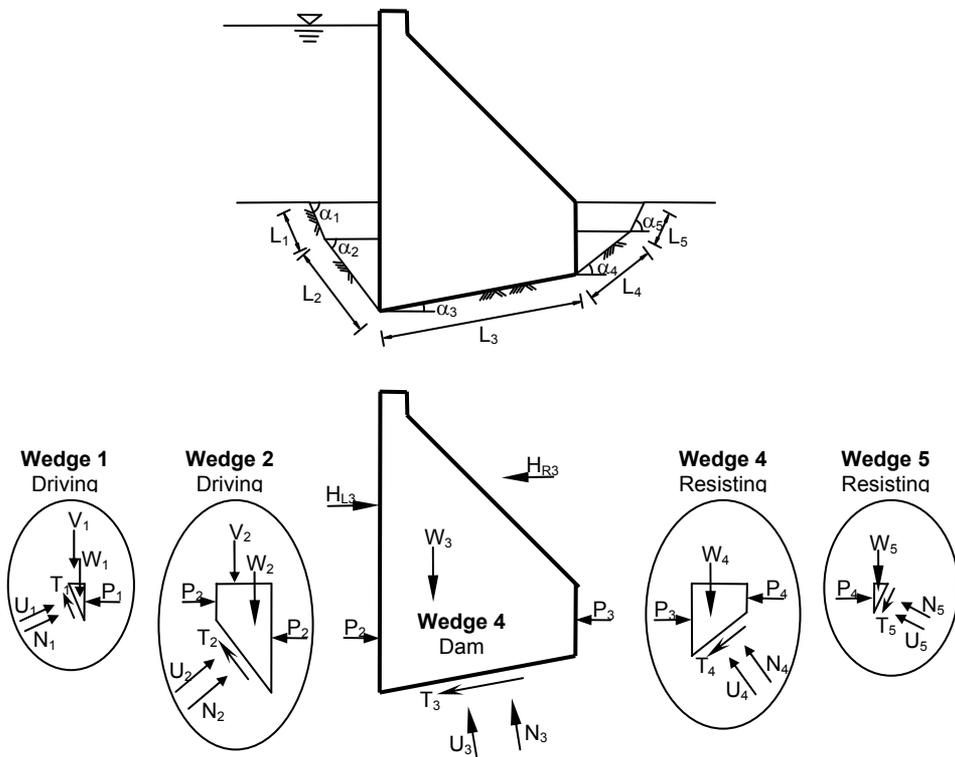


Figure 3. Driving and resisting wedges for dam-foundation system in multiple wedge analysis

$$\tau_F = c + \sigma_N \tan f \tag{4a}$$

Or

$$T_F = cL + N \tan f \tag{4b}$$

Here, τ_F , σ_N , T_F , N , \square and c are shear stress, normal stress, maximum shear resistance, resultant of the forces perpendicular to shear plane, internal friction angle and cohesion, respectively [13]. Also L defines the base length along the slip plane. By this way sliding resistance of every wedge can be obtained;

$$T_F = N_i \tan f_i + c_i L_i \tag{5}$$

Ratio of the sliding resistance to sliding force along the sliding surface (T_i) is expressed by the following;

$$FS_i = \frac{T_F}{T_i} = \frac{N_i \tan f_i + c_i L_i}{T_i} \tag{6}$$

Equations written for sliding stability analysis are based on the right-hand sign convention. The origin of the coordinate system for each wedge is located in the lower left-hand corner of the wedge. When axis that are tangent and normal to failure planes are placed on x-y axis, positive value of angle α developed between the axis are in counter-clockwise rotation.

When (2) and (3) equations are taken into the equation (6) and arranged;

$$(P_{i-1} - P_i) = \{ [A_i \cos \alpha_i - U_i + B_i \sin \alpha_i] C_i - B_i \cos \alpha_i + A_i \sin \alpha_i + D_i \} / [\cos \alpha_i - (\sin \alpha_i) C_i] \quad (7)$$

General multiple wedge system equation is obtained. Here;

$$A_i = W_i + V_i$$

$$B_i = H_{Li} - H_{Ri}$$

$$C_i = \frac{\tan f_i}{FS_i} \text{ and } D_i = \frac{c_i}{FS_i} L_i$$

For driving wedges $\alpha_i = 45^\circ + f_i / 2$ and for resisting wedges $\alpha_i = 45^\circ - f_i / 2$. If $(P_{i-1} - P_i)$ in the equation (7) is negative, forces acting on wedge are exceeding the forces that are resisting to sliding on wedge slip plane. In case of this value is positive then this means that forces along the wedge slip plane are less than the resisting forces [2].

Factors of safety of whole system for sliding equilibrium can be obtained when equilibrium of every wedge is provided. This can be obtained by solving the number (7) equation repeatedly.

5. NUMERICAL APPLICATION

5.1. Sarıyar Concrete Gravity Dam

In this study, Sarıyar concrete gravity dam is chosen for determining sliding stability of a concrete gravity dams by multiple wedge analysis (Figure 4).



Figure 4. A view of Sarıyar concrete gravity dam

This dam is constructed on Sakarya river in Ankara, Nallihan at the year of 1956. Dam was constructed for only energy production and it has 1900 hm³ of reservoir storage. As it can be seen from Figure 5a dam height is 90 m from thalweg level, dam height is 108 m from base, base width of the dam is 72 m and slope of the downstream face is 0,7.

Unit weight of the Sarıyar concrete gravity dam is taken as 24 kN/m^3 and unit weight of the foundation is 22 kN/m^3 for multiple wedge analysis.

Free body diagram of the Sarıyar concrete gravity dam that belongs to dam-foundation system in accordance with the multiple wedge analysis is given in Figure 5b. In this study conducted for researching changes in FS (factor of safety) for different soil properties and loading conditions, soil stratification is neglected. Since there is no adequate drainage in dam base, analysis are performed by considering base pressure. Effects of the seismic zone and changes in cohesion and internal friction of foundation on which the dam will be constructed are examined, separately. In addition, adequate drainage condition at the dam base is examined.

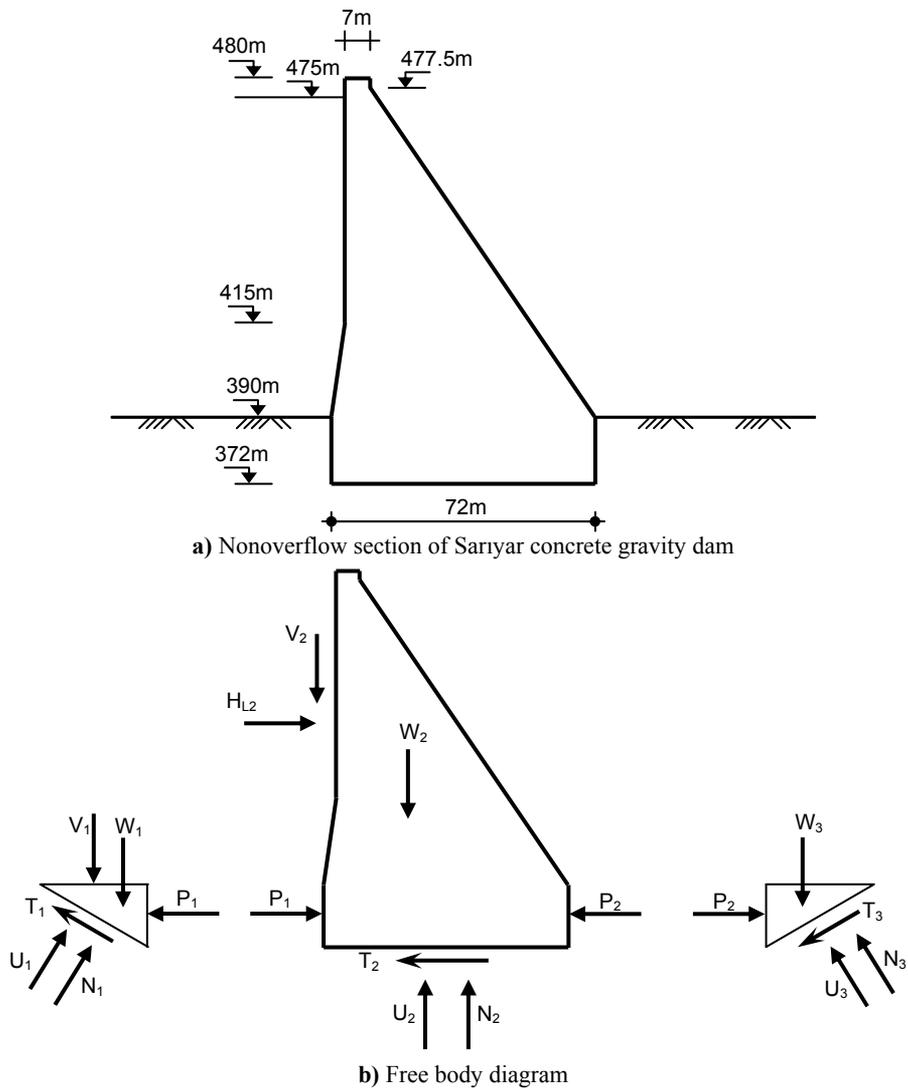


Figure 5. Nonoverflow section of Sarıyar concrete gravity dam (a) and free body diagram (b)

5.2. Effect of Cohesion on Factor of Safety (FS)

For examining the effect of cohesion on FS, internal friction angle is considered as 25° and three different values of dam base angle are considered ($\alpha=-5^\circ$, $\alpha=0^\circ$ and $\alpha=5^\circ$). Usual loading condition and various cohesion values are taken into account and FS results obtained from the analysis are presented in Table 2. Moreover, the changing between summation of applied forces acting horizontally on wedges and FS are given graphically for three different value ($\alpha=-5^\circ$, $\alpha=0^\circ$ and $\alpha=5^\circ$) of dam base angle and different cohesion values in Figure 6.

It is showed in Table 2 that FS value increases when cohesion increases for every value of the dam base angle. As a result of that when base cohesion value increases, FS will also increase. As it can be seen from Figure 6, changing in dam base angle from negative to positive provides decrease in total horizontal forces. This condition has positive effects on FS of the dam.

Table 2. FS values for usual loading conditions and various cohesion values

Cohesion (c, kN/m ²)	FS		
	$\alpha=-5^\circ$	$\alpha=0^\circ$	$\alpha=5^\circ$
500	1,90	2,05	2,30
1000	3,20	3,45	3,80
2000	5,80	6,25	6,90
3000	8,45	9,05	9,95

5.3. Effect of Internal Friction Angle on Factor of Safety (FS)

For examining the effect of internal friction angle on FS, cohesion of the foundation is considered as 3000kN/m² and three different dam base angle ($\alpha=-5^\circ$, $\alpha=0^\circ$ and $\alpha=5^\circ$) are considered. FS values obtained by considering internal friction angle values and usual loading conditions are given in Table 3. Also the changing between summation of applied forces acting horizontally on wedges and FS for three different values of dam base angle ($\alpha=-5^\circ$, $\alpha=0^\circ$ and $\alpha=5^\circ$) due to internal friction angle is given in Figure 7.

Table 3. FS values for usual loading condition and various internal friction angle values

Internal Friction Angle (ϕ)	FS		
	$\alpha=-5^\circ$	$\alpha=0^\circ$	$\alpha=5^\circ$
20°	8,30	8,90	9,80
25°	8,45	9,05	9,95
30°	8,60	9,20	10,00
35°	9,75	9,40	10,30

When Table 3 is examined, it is seen that FS value increases for increasing of the internal friction angle just like in the cohesion effect. Therefore, it can be said that FS value of the dam will also increase when internal friction angle of the foundation increases. Also as it can be seen in Figure 7 changing in dam base angle from negative to positive causes decrease in total horizontal forces in the system. This also have positive effects on FS value of the dam.

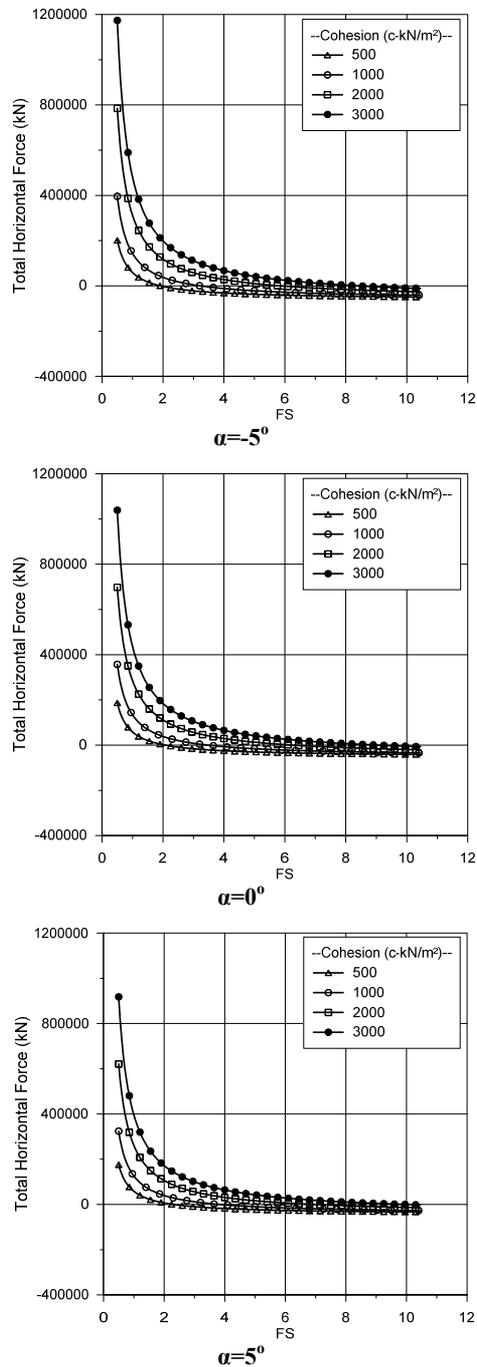


Figure 6. Graphics for changes between FS and total horizontal forces ($\Sigma\Delta P$) for three different values of dam base angle ($\alpha = -5^\circ$, $\alpha = 0^\circ$ and $\alpha = 5^\circ$) depending on cohesion

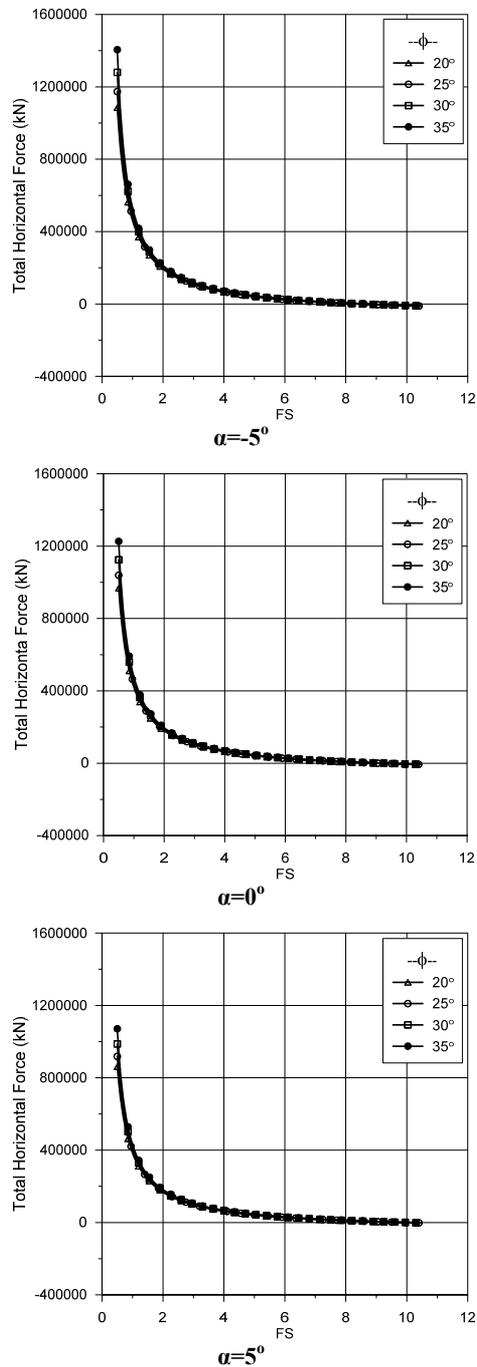


Figure 7. Graphics for changes between FS and total horizontal forces three different values of dam base angle ($\Sigma\Delta P$) for ($\alpha = -5^\circ$, $\alpha = 0^\circ$ and $\alpha = 5^\circ$) depending on internal friction angle

5.4. Effect of Seismic Zones on the FS

While examining the effects of seismic zones to FS, internal friction angle of the foundation is taken 25° , cohesion is taken 3000 kN/m^2 and three different values of dam base angle are taken into consideration as $\alpha=-5^\circ$, $\alpha=0^\circ$ and $\alpha=5^\circ$. FS values that are obtained from the analysis of four seismic zones [14] are shown in Table 4. For three different dam base angle ($\alpha=-5^\circ$, $\alpha=0^\circ$ and $\alpha=5^\circ$), changes in FS and total horizontal forces are shown in Figure 8 according to seismic zones.

When Table 4 is examined, it is seen that when effective ground acceleration coefficient (A_0) increased, FS value is also increased for every value of it. This result is expected. Since the earthquake force is a horizontal force and decrease of effective ground acceleration means decrease of earthquake forces so that FS is in tendency to increasing. Also as it can be seen in Figure 8 changing of dam base angle from negative to positive causes decrease in total horizontal forces in the system. This can have positive effect on FS value of the dam.

Table 4. FS values obtained for four different earthquake regions

Seismic zone	Effective Ground Acceleration Coefficient (A_0)	FS		
		$\alpha=-5^\circ$	$\alpha=0^\circ$	$\alpha=5^\circ$
1	0,40	4,15	4,15	4,20
2	0,30	4,75	4,80	4,90
3	0,20	5,55	5,70	5,90
4	0,10	6,70	7,00	7,40

5.5. Effect of Uplift Pressure on FS

Drainage system is very important on the sliding stability of concrete gravity dams due to the great base pressures in regions which is no drainage system. While the effect of uplift pressure on FS is examined then internal friction angle of foundation is taken as 25° , cohesion is taken as 3000 kN/m^2 and three different values of dam base angle are considered as $\alpha=-5^\circ$, $\alpha=0^\circ$ and $\alpha=5^\circ$. FS values obtained from the results of the analysis in which there is adequate drainage or not drainage in the dam base for first degree seismic zone ($A_0=0,40$) are shown in Table 5. For three different values of dam base angle ($\alpha=-5^\circ$, $\alpha=0^\circ$ and $\alpha=5^\circ$), changing between FS and total horizontal force are given in Figure 9 according to drainage in the dam base.

When Table 5 is examined it is seen that FS value decreases for inadequate drainage condition due to every value of the dam base angle. It can be said from here that base pressure has a detractive effect on sliding stability. Also as it can be seen from Figure 9 changes in dam base angle from negative to positive caused decrease in total horizontal force both in adequate drainage condition and inadequate drainage condition. This can also have positive effect on FS of the dam.

Table 5. FS values obtained with drainage and without drainage in the dam base

With Drainage			Without Drainage		
FS			FS		
$\alpha=-5^\circ$	$\alpha=0^\circ$	$\alpha=5^\circ$	$\alpha=-5^\circ$	$\alpha=0^\circ$	$\alpha=5^\circ$
4,30	4,35	4,40	4,15	4,15	4,20

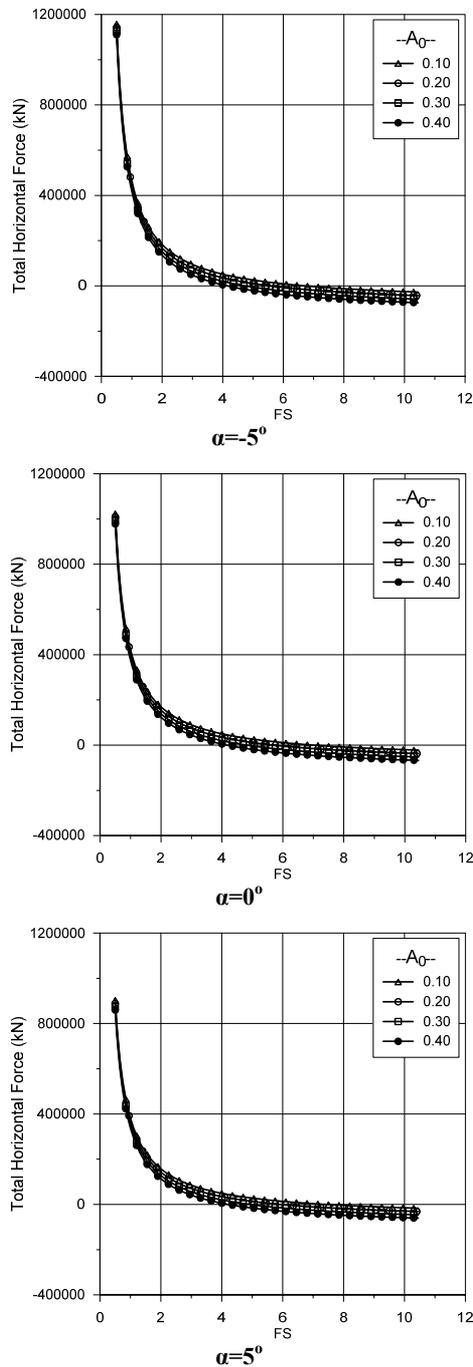


Figure 8. Graphics for changes between FS and total horizontal forces ($\Sigma\Delta P$) for three different values of dam base angles ($\alpha = -5^\circ$, $\alpha = 0^\circ$ and $\alpha = 5^\circ$) depending on seismic zones

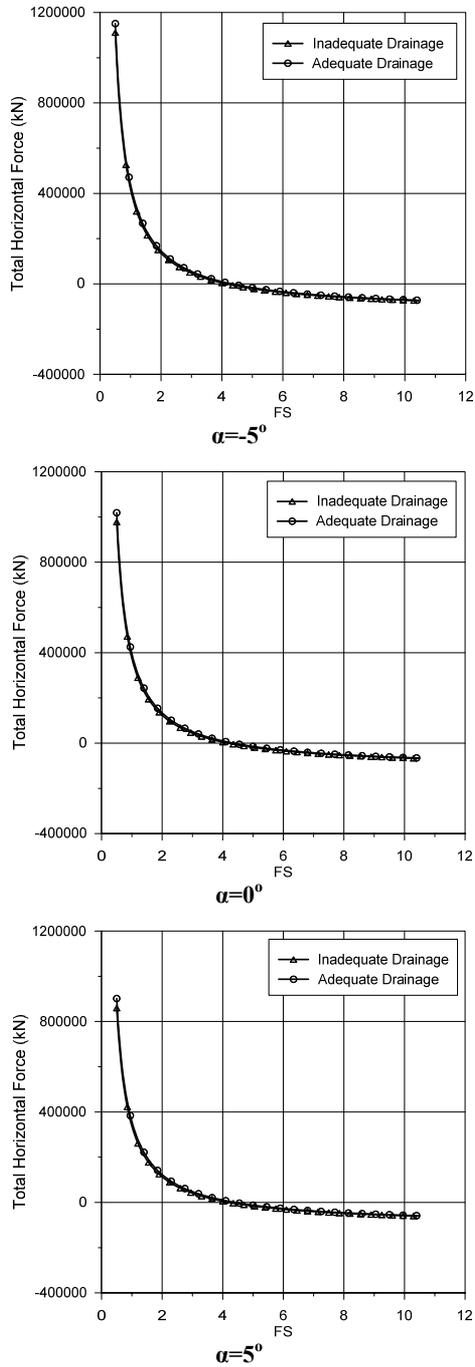


Figure 9. Graphics for changes between FS and total horizontal forces ($\sum \Delta P$) for three different values of dam base angles $\alpha = -5^\circ$, $\alpha = 0^\circ$ and $\alpha = 5^\circ$ depending on drainage in the dam base

6. RESULTS

In this study, sliding stability of the concrete gravity dams is evaluated using Multiple Wedge Analysis approach that based upon Mohr-Coulomb Failure Criterion. Sariyar concrete gravity dam is chosen as a numerical application. The effects of the parameters which are dam base angle, cohesion and internal friction angle of soil, uplift pressure and earthquake loads on the sliding stability of the dam are investigated.

Some considerations are presented according to analysis results as the following;

1) Hydrodynamic water forces acting on the dam in the operating process of the dam and earthquake force acting dam for seismic zone are the most effective parameters in the dam sliding stability.

2) Cohesion and internal friction angle values of the soil interacting with the dam are two important parameters determining the sliding stability of the dam. Because of this reason, cohesion and internal friction angle values of the soil on which the dam is built are very important for determining of dam and dam base geometry.

3) Uplift pressure has a detractive effect on dam sliding stability.

4) Changes from negative to positive in dam base angle affect the sliding stability in positive manner. Since the dam structure is the greatest and most effective wedge which resists to sliding, positive base angle is a positive parameter for factor of safety against sliding.

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