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Sensitivity Analysis of Earthquake Acceleration and Drainage Efficiency on the Stability of Weighted Concrete Dams

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Abstract— **Dams are one of the biggest and most important structures that are built by mankind to meet different purposes in particular optimal exploitation of the water resources in the desired area. Failure of this type of structure can lead to catastrophic damages to the downstream side of the dam. Therefore, great accuracy and attention in designing and maintaining the stability of these structures are of crucial importance. One of the most important debates is maintaining the stability of dams against sliding and overturning. In this research, the effect of earthquake acceleration as well as the efficiency of drainage in weighted concrete dams in different loading modes has been analyzed on the overturning safety factor and slipping safety factor of stability by using numerical modeling. The results indicate that by increasing the efficiency of drainage, the overturning and Slipping Safety Factor increase at the dam toe and this leads to better stability of the dam. Also, increasing the earthquake acceleration reduces the overturning safety factor and Slipping Safety Factor and leads to dam instability; dam instability is occurred by increased driving force. In general, it can be concluded that the effect of increased earthquake acceleration on the stability safety factor is far more than the effect of increased efficiency drainage on these factors.**

Index Terms - **CADAM Software, Earthquake Acceleration, Sensitivity analysis, Stability against Overturning, Stability against Slipping, Weighted Concrete Dam.**

I. INTRODUCTION

Different types of infrastructures like hydraulic structures, buildings, railways etc. are widely investigated for the stability issues regarding different possible loading scenario by many researchers in all around the world [1-8]. Dam is one of the most important and expensive infrastructures. One of the important debates in the design of weighted concrete dams is dam stability which should be investigated from two aspects: overturning stability analysis of the structure and the slipping stability analysis. Of course, during the above analysis, stress analysis should also be performed. So far, many studies in this field have been done by researchers such as Javanmardi et al., who investigated the seismic stability of weighted concrete dam with regard to the uplift force in the cracks, and stated that the entrance length of water into the dam body and the overall amount of uplift force affecting the cracks decreases with the crack opening and increases with the crack closure. A weighted concrete dam was analyzed with a height of 90 meters subjected to two varying earthquake accelerations, and it was founded that the magnitude of the uplift force is small when the cracks are being opened, as well as the Slipping Safety Factor (SSF) at the downstream side of the dam in crack opening is similar to the SSF in the absence of any uplift force in the crack [9]. Javanmardi and Lager also carried out a similar study to the previous study and examined the seismic stability in weighted concrete dams that were strengthened by making an embankment. Making an embankment at the downstream side of the dam means to increase dam stability against seismic and hydrostatic loads. In a study conducted by these researchers, a weighted concrete dam with a height of 35 meters was investigated and the results show that making an embankment behind the dam has improved the seismic resistance of the dam against hydrological loads [10].

Leclerc et al. also examined the seismic and static stability of weighted concrete dams using a CADAM software. CADAM software is based on gravity method (rigid body equilibrium and beam theory) to perform stress analysis, compute cracks and safety factor [11]. Hua San et al. is another researcher who studied dam's stability. They studied three-dimensional methods for the stability of weighted concrete dams [12]. Teng-fei et al investigated the stability of the foundation in weighted concrete dams weights based on plastic strain energy method [13]. Zhouji Huang investigated the seismic performance of weighted concrete dams subjected to different earth seismic movements, which expanded the finite element method used for experiments performed on the seismic table; the results showed different response patterns for uniform and non-uniform seismic movements. It has been shown that in non-uniform conditions, there are more openings in the heel of the dam and more slipping in the toe of the dam [14].

Baghlani and Sattari examined the stability of weighted concrete dam based on the incremental loading analysis using CADAM. In this research, the maximum horizontal acceleration of the earthquake and the height of the water at the upstream side of the dam were increased gradually and analyzed their effects on the stability of the dam [15].

Sabzevari performed stability analysis on Pine Flat Dam by CADAM software. In this research, a full reservoir with

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flexible foundation, an empty reservoir with flexible foundation, a full reservoir with rigid foundation and empty reservoir with rigid foundation were examined and stated that the response of dam structure with full reservoir and flexible foundation is more than the response of dam with an empty reservoir and rigid foundation. This means that the interaction between dam and lake and the beneath stone bed would increase the response of the structure against the earthquake [16].

Maddenost et al. examined the stresses on the dam body during an earthquake and at different levels of water using the neural network and stated that the water balance ratio is the most important factor in changing the stress in the dam body [17].

Also, the researchers in another study investigated the earthquake force on the dam according to different levels of water and stated that due to changes in water heights, stress in the half-height of the dam decreases when the height of water in the reservoir decreases up to the half and afterward remains relatively constant [18]. Siamardi stated that pseudo-dynamic analysis can provide an appropriate response for weighed concrete dams [19]. Sensitivity analysis is extremely useful when the sensitivity of weighted concrete dam stability responses in response to the desired parameters of interest is intended. Sensitivity analysis has been successfully used in detecting the most influential parameters in other structure types [20].

In this study, a weighted dam is modeled in CADAM and the results of sensitivity analysis of drainage efficiency and earthquake acceleration are compared to each other. The results indicate that the changing in earthquake acceleration is more effective than the changing in drainage efficiency on stability safety factor.

II. METHODOLOGY OF THE STUDY

In the recent study, CADAM (Computer Analysis of Dams) software has been used to determine the effect of earthquake acceleration, as well as the efficiencies of drainage systems in the weighted concrete dams in different loading conditions on stability against overturning and slipping. The loading type 6 in the USACE code where the depth of the upstream water is at the normal level and the depth of the base is minimum, as well as the maximum earthquake (MCE) and its direction is also downward has been used to confirm and validate the results obtained from the software. So that, the calculations for determining the values of sustainability including forces and their resultant location as well as the stability factor are obtained manually and using analytical relationships as well as using the CADAM software and are compared together for validation.

A. *Different Load Combinations and Allowed Safety Factor for Stability Analysis According to USACE*

According to United States Army Corps of Engineers (USACE) code, seven different types of load combinations should be considered. The reader is referred to the code for the exact definition of each combination. The loading combination that is considered in this study are as follow: Load combination No. 2 is of the ordinary type and the dam is in normal operation. The height of the water in the reservoir is upstream lock gate while controlling spillway gate and is spillway crown when the spillway gate is not controlled. The depth of the base is at least and is considered if there are deposition or ice forces. Load combination 3 is of an unusual type and the dam is under flood discharge effect. The reservoir is in standard flood mode and the gates are open flood controlled, the base is located at the flood height, the uplift force is calculated, if deposition force is applied, ice force is not applied. These two load combinations are provided with static loads, and the earthquake force has not been applied on these loads and has been used in recent research. The earthquake force has been applied in the load combination of 4 to 7, which only the combined loads No. 5 and 6 have been used in the recent research out of these four load combinations. Load combination No. 5 is an unusual load type and the dam is in the normal operation and earthquake OBE phase. The earthquake acceleration is applied downstream, the water's height in the reservoir is at normal and the base depth is at least. The life force is applied in the pre-earthquake mode, and if there is a deposition force, it does not have ice forces. Load combination No. 6 is of the Extreme load type and the dam is in the normal operation stage under the maximum considered earthquake (MCE). The horizontal acceleration of the earthquake is in the downstream direction, the water height in the reservoir is at a minimum depth and the base depth is at least. The uplift force is applied in the pre-earthquake mode, and if there is a deposition force, it does not have ice forces. Table 1 shows allowed safety factor for stability analysis in different modes.

For each load combination, the Overturning Safety Factor (OSF) and also vertical stress in the soil is obtained by CADAM software. For calculations by the software, the geometric model of the dam should be defined in the software at first, and then adjustments for static loads including the height of water in the reservoir at upstream and downstream sides of the them (in normal or flood conditions), the sediment load, ice, and etc. if exist should be defined in the software. In the next step, the factors affecting the uplift force level such as drainage efficiency, etc. are defined in the software. After defining static loads, seismic loads, if exist, must be defined and analyzed in static and dynamic modes. In the next step, the manner for developing the crack and its effect on the uplift is explained, then the composition of the load and the

Table 1 - Allowed Safety Factor for Stability Analysis

Load Condition	Resultant Location in Base	Foundation Bearing Force	Minimum OSF	OSF
Usual	⅓ Middle	Allowed ≤	2	1.2
Unusual	½ Middle	Allowed ≤	1.7	1.2
Extreme	Along the Base	≤Allowed× 1.33	1.3	1.1

coefficients for each load that is one of the four load combinations at the previous stage is defined in the software. Finally, the model calculations are performed and outputs are obtained from the software. Also, the results are controlled by authorized values. This software has the ability to perform the sensitivity analysis by changing the parameters step by step (incremental load analysis). Therefore, the resultant location of a specific variable on the results can be determined.

III. NUMERICAL MODEL PARAMETERS

The dam with specification as sketched in Fig. 1a and b are considered and analyzed. The specific gravity of the concrete is 2400 kg/m^3, the internal friction angle of the soil is 45 degrees, and the soil adhesion is equal to 0.3. Also, the normal depth of water at the upstream side of the dam is 143 meters and the depth of water in the flood standard is 148 meters. The depth of the base is also zero in relation to the desired loading. The sediment depth at the back of the dam is 10 meters with a specific gravity of 18.83 kN/m^3 and a rest silt force is 0.7.

For the dam under the study, horizontal earthquake acceleration in OBE mode is 0.2 and in MCE mode is 0.58. The effect of vertical earthquake acceleration is also neglected.

USACE code was used to calculate the effect of the drainage on the uplift force, and at the beginning, the maximum drainage efficiency is 0.67. Chopra method is used for seismic dynamic calculations, and earthquake acceleration is multiplied by a discount factor of 0.67 for computing stresses. Also due to the upstream inclination, it should be changed to a flat state. For correcting non-orthogonal upstream of the dam between the two and USBR methods provided by Corns et al, the first method is selected. If the effect of cracking is supposed to be taken into account, the effect of cracking on the uplift force is shown in Figure. 3 according to the various regulations.

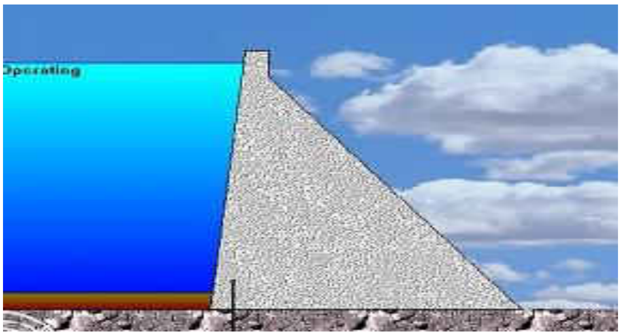

Fig. 1 - Model of Dam in CADAM Software (Load Combination 6).

Table 2 - The Results of Software for Load Combination 2.

Control	Allowed	Value	Characteristic	
Ok	-9990	-1914.79	σd	Stress in The Toe
Ok	-9990	-1111.05	σu	Stress in The Heel
Ok	2>	2.39	SSF	Slipping Safety Factor
Ok	1.2>	2.4	OSF	Overturning Safety Factor
Ok	⅓ Middle	61.05	RL	Resultant Location
		0	Crack%	Cracking Percentage

Table 3 - The Results of Software for Load Combination 3.

Control	Allowed	Value	Characteristic	
Ok	-9990	--2084.22	σd	Stress in The Toe
Ok	-9990	-933.55	σu	Stress in The Heel
Ok	1.7>	2.23	SSF	Slipping Safety Factor
Ok	1.2>	2.24	OSF	Overturning Safety Factor
Ok	½ Middle	57.98	RL	Resultant Location
		0	Joint Crack%	Cracking Percentage

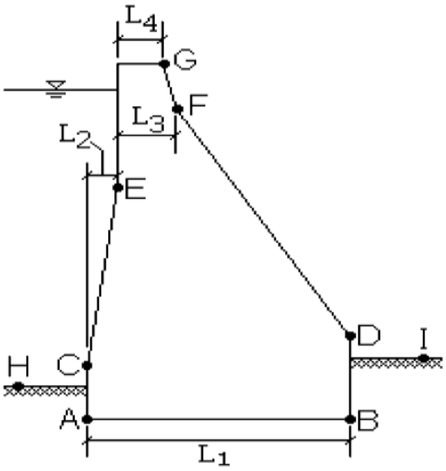

Fig. 2 - Dimensions of the Dam: L_1: 133 m, L_2: 15 m, $L_{3,4}$: 10 m, ELV $_G$: 150 m.

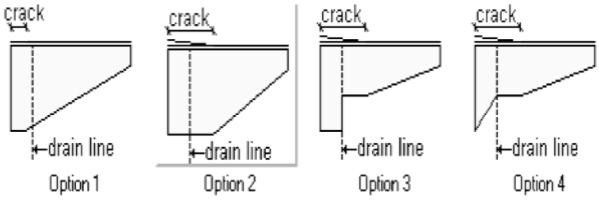

Fig. 3- The Effect of Cracking on the Uplift Force [21].

A. Calculation of SSF by analytic relationships and software for combining load No. 6:

The loads on the dam are divided into two general categories of the forces acting in favor of the dam stability and the forces acting in favor of the dam instability as shown in Fig. 4.

B. Forces Acting in Favor of the Dam Instability

Forces considered in this study alongside with their establishing equation s are presented here:

- Horizontal water force in the direction of water movement;

$$F = \frac{1}{2}\gamma h^2 \tag{1}$$

- The force generated by the waves in the reservoir of the dam which will not be discussed in this topic;
- Sediments force in the direction of the horizon;

$$F_{sH} = \frac{1}{2}\gamma_s h_s^2 K_0 \tag{2}$$

- Uplift force;
- Force caused by the earthquake in dam body;

$$F_e = \alpha w \tag{3}$$

- Earthquake force in the reservoir of the dam;

$$F_e' = \frac{2}{3} k_\theta c_e \alpha h_w^2 \tag{4}$$

$$c_e = \frac{7.99}{\sqrt{1 - 7.75\left(\frac{h_w}{1000t_e}\right)^2}} \tag{5}$$

$$k_\theta = cos^2\theta \tag{6}$$

- Force caused by earthquake on sediment.

Possible ice-induced force and force generated by the waves in the reservoir of the dam are not considered in this study.

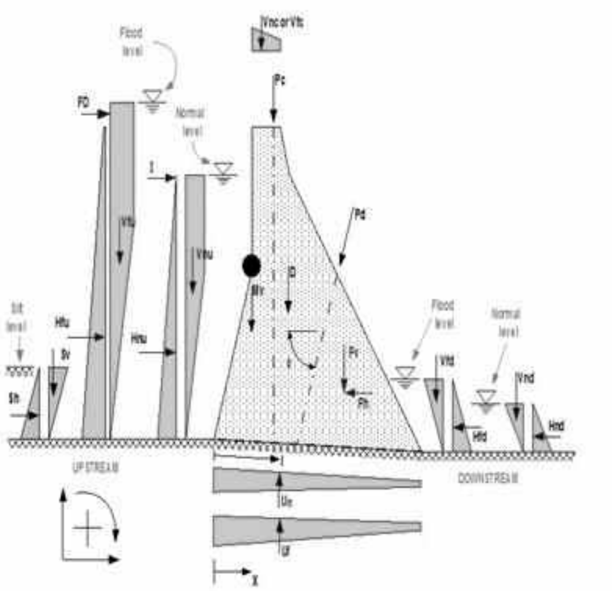

Fig. 4 – Loads on the Dam Stability and Instability [21].

D. Calculating the SSF

For this purpose, first of all, the resultant location and the probability of the occurrence of the crack should be examined. In the cracking, the modified length should be considered to calculate the SSF.

In software settings, we assumed that seismic loads did not change uplift force.

E. Calculate Resultant Location:

The distance of 24.99 m from the toe of the dam (Fig. 5) due to the extreme nature of the load in the load combination 6 indicates the resultant location in the base and is acceptable.

F. Estimation of Eccentricity

Performing stress analysis, the length of crack is estimated as 30.99 m. The crack length is used for estimating SSF and estimated to be 0.976.

Table 4 - The Results of Software for Load Combination 5.

Control	Allowed	Value	Characteristic	
Ok	-9990	-3215.9	σd	Stress in The Toe
Ok	-9990	-0.002	σu	Stress in The Heel
Not Ok	1.7>	1.603	SSF	Slipping Safety Factor
Ok	1.1>	1.84	OSF	Overturning Safety Factor
Ok	½ Middle	48.09	RL	Resultant Location
		7.015	Joint Crack%	Cracking Percentage

C. Calculate Overturning Safety Factor

Stability against overturning and slipping is calculated by resisting forces divided by driving forces. The anchors can be placed around the toe or heel of the dam, but it is better to place the anchors around the dam for all loads combination except No. 4 where the reservoir is empty and direction of earthquake force is upstream and only anchors in load combination No. 4 are placed in the hell of the dam. The calculated anchors in the previous steps for load combination No. 6 were all around the toe of the dam that we use it now:

The SSF is less than the allowed limit for Extreme loads (1.3). Also, the obtained safety factor is a little bit more than the amount calculated by the software which is due to the difference in the length of the crack calculated by the manual and software calculations. In manual calculations, the length of the crack is obtained from the analytic stress relationship, but the software uses repetition method for computing the length of the crack. At first, a certain value is assumed and examines its accuracy. If it is correct, it chooses it as the length of the cracks, and if it does not meet the conditions, the new value is re-assumed which is a more precise method.

In Table 6, manual estimation for load combination 6 is compared with results obtained by Software; seismic forces are shown with earthquake acceleration and discount factor.

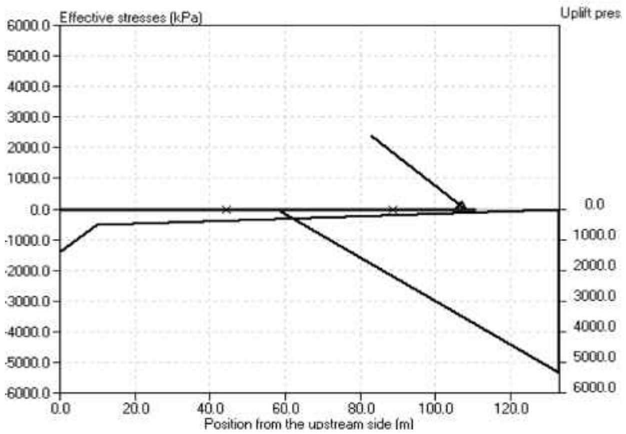

Fig. 5 - Resultant Location of the Load Obtained in CACAM Software for Load Combination 6.

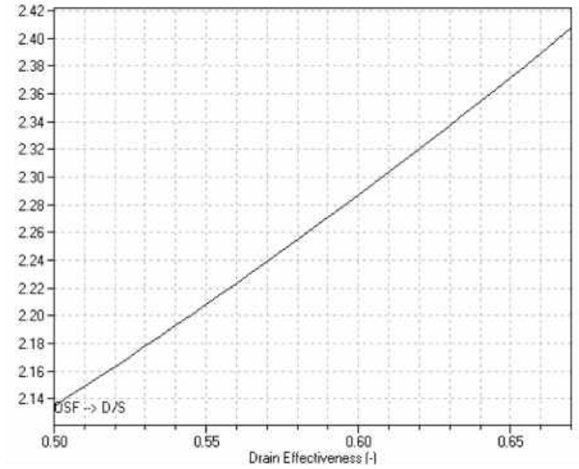

Fig. 6 - Gradual Increase of Drainage Efficiency and its Effect on OSF Load Combination No. 6.

IV. DISCUSSION

As the first case for load combination 6, the drainage efficiency is increased by a step of 0.05 from 0.5 to a maximum of 0.67, and its effect on static loads and some other parameters is examined. As it is known, with increasing the drainage efficiency, the SSF increases and this provides better stability against slipping. The reason is that by increasing the drainage efficiency, the uplift force decreases and consequently in the associated Equation for SSF calculation, the numerator increases and this increases the total amount of deductions and SSF considering the constant total horizontal forces. The Figures of changes in drainage efficiency with OSF and SSF are plotted in Fig. 6 and 7 respectively.

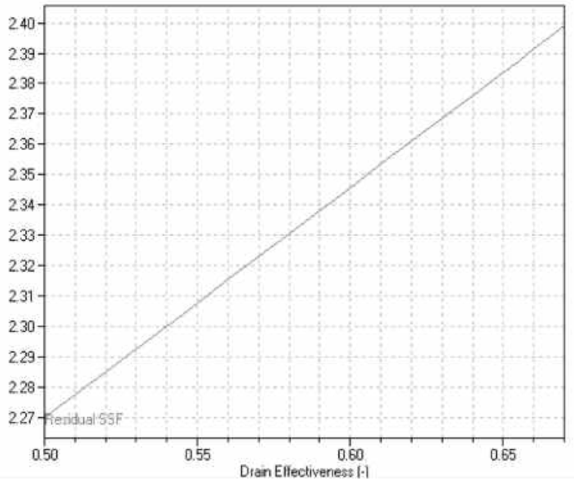

Fig. 7- Gradual Increase of Drainage Efficiency and its Effect on SSF for Load Combination No. 6.

The reason for increasing the amount of OSF by increasing the drainage efficiency is that by constant numerator in the OSF Equation and reduced denominator due to the decrease of the uplift force, the overall numerator increases and the

Table 5 - The Results of Software for Load Combination 6

Control	Allowed	Value	Characteristic	
Ok	-27270	-17868.28	σd	Stress in The Toe
Ok	-9990	-0.032	σu	Stress in The Heel
Not Ok	1.3>	0.876	SSF	Slipping Safety Factor
Ok	1.1>	1.317	OSF	Overturning Safety Factor
Ok	Along the Base	25.92	RL	Resultant Location
		83.06	Joint Crack%	Cracking Percentage

Table 6 - The Analytical and Software Results for Load Combination 6

Load	Manual Value	Manual Resultant Location (M)	Value in Software	Software Resultant location (M)	Control
Weight	233438.76	X=49.01	233438.76	X=49.01	OK
Horizontal Water Force	100302.34	Y=47.67	100302.34	Y=47.66	OK
Vertical Water Force	10030.23	X=4.77	10030.23	X=4.76	OK
Horizontal Sediment Force	315.95	Y=3.33	315.95	Y=3.33	OK
Vertical Sediment Force	45.135	X=0.333	45.13	X=0.33	OK
Eq. Force of Body	90714.3	Y=50.11	90807.67	Y=50.1	OK
Eq. Force of Water	45696.88	Y=57.2	45733.75	Y=57.2	OK
Eq. Force of Deposition	205.13	Y=4	188.78	Y=4	OK
Uplift	42424.73	X=40.34	42295.81	X=40.31	OK

Table 7 - The Analytical and Software Results for Load Combination 6

	Manual	Software	Control
SSF	0.976	0.876	OK-But not allowed
OSF(D/S)	1.317	1.317	OK

number of OSF increases and provides a better stability for the dam against overturning. Comparison of two Figures, it can be concluded that the incremental inclination in the OSF is greater than SSF.

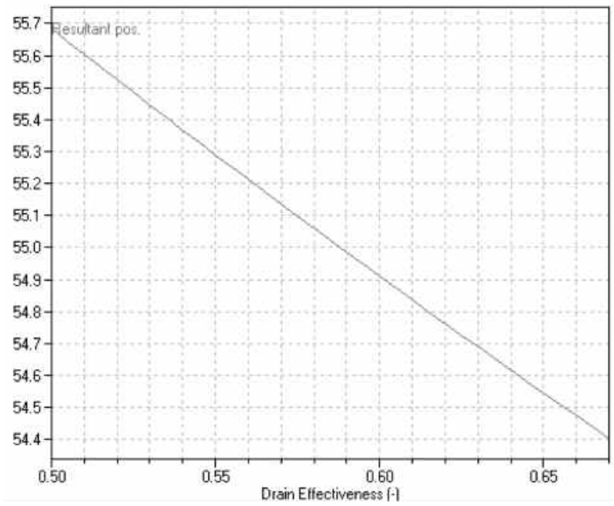

Fig. 8 - Gradual Increase of Drainage Efficiency and its Effect on Uplift Force Changes for Load Combination No. 6.

Fig. 8 shows that the change in drainage efficiency and consequently, the change in uplift slightly leads to the displacement of the resultant forces. The second factor is the horizontal acceleration of the earthquake with a step of 0.005 with 0.25 for the OBE. In this study, the maximum considered earthquake (MCE) increase to 0.58 as shown in Fig. 9.

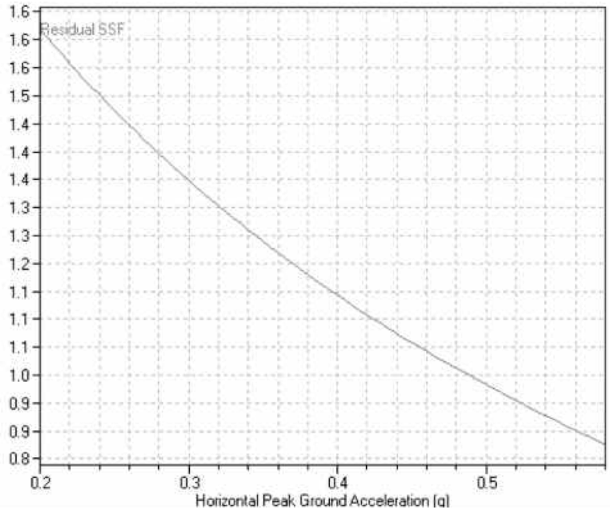

Fig. 9- Gradual Increase of Earthquake Acceleration and its Effect on OSF at the Upstream for Load Combination No. 6.

In the case of changes in the OSF and slipping (downstream), it can be stated that by increasing the earthquake acceleration, the values of SSF and OSF decrease dramatically and cause dam instability for increasing the driving force due to an increase of earthquake acceleration. As shown in the Figure, OSF changes are somewhat more than SSF. It was observed that the increase in the earthquake acceleration significantly changes the resultant location in the last parameter studied in the earthquake acceleration. Up to this stage, it can be concluded that the effect of increasing the earthquake acceleration on other parameters is far more than the effect of increasing the drainage efficiency on other parameters.

V. CONCLUSION

In this research, the effect of earthquake acceleration as well as the efficiency of drainage in weighted concrete dams in different loading combinations have been analyzed on the overturning and SSF of stability by CADAM software and the results indicate that by increasing the efficiency of drainage, the overturning and SSF increase at the dam toe and this leads to better stability of the dam. Also, increasing the earthquake acceleration reduces the overturning and SSF and leads to dam instability; dam instability is occurred by increased driving force. In general, it can be concluded that the effect of increased earthquake acceleration on the stability safety factor is far more than the effect of increased efficiency drainage on these factors.

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