Indian Geotechnical Journal, 40(1), 2010, 38-46

Seismic Coefficient of Pseudo-Static Analysis for Masjed Soleiman Dam

A. Ghanbari[1], M. Davoodi[2] and B. Ahmadi[3]

ABSTRACT: Pseudo-static analysis is a common and simple method to study the seismic stability of earth dams. Precise selection of the horizontal acceleration coefficient is the primary step in the evaluation of seismic behavior of earth dams using the pseudo-static method. Previous researchers and design manuals of earth dams often suggest constant values for selecting the seismic coefficient regardless of site seismicity and the dynamic characteristics of the structures. In order to improve the available methods, a new equation is presented to determine the pseudo-static coefficient of earth dams. In this equation, variations in acceleration with the height of the dam are considered to be linear and the gradient of this line is related to the geometrical characteristics of the dam body, soil stiffness and damping values. The input acceleration amplitude is determined based on the seismic conditions of the region and site effects. In order to evaluate the coefficients of this equation, pseudo-static, static and dynamic analyses of the Masjed Soleiman earth dam are performed.

KEYWORDS: Earth dam; Pseudo-static; Dynamic analysis; Horizontal acceleration coefficient; Seismicity

Introduction

The methods for seismic stability analysis of embankment dams can be categorized as numerical, laboratory or field. Using mathematical techniques and suitable behavior models, numerical methods are used to predict dam behavior under applied loads. Different numerical methods can be used to perform a seismic response analysis of an embankment dam. Generally, these methods are divided into two major categories: techniques in which the dynamic response of a dam is obtained; and techniques in which dam stability is studied. In the first technique, the dynamic response of the system is obtained using the finite element or finite difference method or methods with simple assumptions such as the uniform distribution of shear stress in horizontal planes (shear beam method). In stability analysis methods with simple assumptions, the safety factor of the slope stability is obtained.

Despite the existence of the above mentioned techniques, the pseudo-static method is the primary requirement of seismic design manuals and the simplest method seismic analysis. Pseudo-static analysis is don e on the basis of common theories of slope stability analysis with an additional constant force which represents earthquake excitation. Generally, it is assumed that the earthquake force equals K_hW, where W is weight of the sliding mass. K_h is the horizontal acceleration coefficient (for which researchers have presented different values). In the stability evaluation of the dam body, this force is considered to be accompanied by other applied forces on the sliding mass.

Pseudo-Static Seismic Coefficient

One of the oldest recommendations for determination of the pseudo-static seismic coefficient was presented by Terzaghi (19950). For the seismicity level of a region, he proposed this coefficient as being between 0.1 and 0.5. Seed (1979) indicated that, for earth filled dams with deformable materials (dams that, in earthquake conditions, do not produce much pore water pressure or experience strength reduction of more than 15% in cyclic loading) and crest accelerations of less than 0.75g, it is only necessary to do pseudo-static analyses using K_h = 0.1 for earthquakes with magnitudes of M = 6.5 or K_h = 0.15 for earthquakes with magnitudes of M = 8.25. In this case, for allowable displacement, the safety factor should be equal to at least 1.15.

Marcuson(1981) suggested that for dams, the pseudo-static coefficients should be 0.33PGA to 0.15PGA, considering wave amplification or reduction effects. In these states, the minimum allowable safety factor is equal to one. Hynes-Griffin and Franklin(1984), using a Newmark sliding block analysis for more than 350 seismographs, concluded that earth filled dams with pseudo-static safety factors higher than one and K_h equivalent to half of the maximum acceleration of the earthquake will not have important and dangerous deformations (about 1m).

The Indian Institute of Technology of Kanpur (2005) proposed the seismic coefficient of pseudo-static analysis to be ZIS/3. In this equation, Z is the seismic coefficient of a particular region as defined in the IS 1893 (2002) and I is the embankment importance factor having a value of between 1 and 2. S is the experimental factor indicating the amplification of earth motion from the bedrock to the toe of the dam or fill and which changes in the India Manual from 1 to 2 in relation to regional seismicity.

In addition to these researchers, Makdisi and Seed (1978) have provided diagrams for the calculation of displacement of the dam crest based on numerical analyses and information obtained from studies of eight strong earthquakes.

1 Tarbiat Moallem University, Mofatteh St., No. 49, Tehran, Iran, E-mail: Ghanbari@tmu.ac.ir
2 International Institute of Seismology and Earthquake Engineering, N. Dibaji St., Arghavan St., No. 26, Tehran, Iran
3 Tarbiat Moallem University, Mofatteh St., No. 49, Tehran, Iran

Proposed Method for Estimating the Horizontal Acceleration Coefficient

The basic assumptions used to calculate a suitable equation for a pseudo-static seismic analysis coefficient in the present study are as follows:

- The pseudo-static coefficient of horizontal acceleration for earth fill dam analysis is a function of dam site seismicity conditions and foundation effects. For this purpose, a basic acceleration parameter (A) has been used which is equivalent to the maximum basic acceleration parameter at the 475-year level and has been introduced in structural design manuals for different regions.
- Since numerical studies indicate acceleration increase with dam height, the seismic coefficient of pseudo-static analysis is assumed to be variable for height. Thus, the seismic coefficient of the foundation and buried sections of the dam will be constant and will increase in elevation linearly. The maximum seismic coefficient will be at the dam crest elevation.

Proposed Equation

Based on the above assumptions, the pseudo-static horizontal acceleration coefficient for seismic analysis of earth fill dams is defined as function $K_h(z)$, where $K_h(z)$ at the dam foundation level (on the alluvium) is equal to base seismic coefficient K_{hb}. Thus:

$$K_{hb} = \alpha A \quad (1)$$

$$K_h(z) = K_{hb}(1+\beta z) \quad (2)$$

In these equations, $K_h(z)$ is a function of the seismic pseudo-static coefficient, which increases linearly from the foundation to the crest of the dam and is marked as K_{hw}. This increase coefficient relates to dam geometrical conditions and material damping. K_{hb} is the base pseudo-static coefficient dependent on the seismicity conditions of the site and foundation effects. Parameter A, the design base acceleration ratio, is equal to the maximum design acceleration (MDE) with a 475-year return period and indicates site seismicity effects.

Parameter α is the ratio of the design base acceleration coefficient to the static equivalent acceleration, which varies from 0.3 to 0.6 with site effects. Parameter β is a factor that expresses the effect of the dam geometry on magnification of the base seismic coefficient and the effects of the geotechnical properties of the dam body material and usually varies between 0 and 1.5. In this regard, maximum seismic coefficient at the crest is 2.5 times greater than the horizontal acceleration coefficient at the base of the dam. The same value (the ratio of maximum crest acceleration to base acceleration) is used in manuals such as the Japan manual for designing earth fill dams resistant to earthquakes (Ozkan, 1998). $z = y/h$ indicates the coordinates of the intended point on the height of the dam. The origin of the coordinates for parameter y is on the dam base and h is the height of the dam. Thus, for the dam crest, $z = 1$.

Derivation of the Parameters of the Proposed Method

In the proposed method, the seismic coefficient is a function of parameters α and β. Parameter β is indicative of acceleration amplification in the direction of the dam height and is related to the geometrical specifications and material properties of the dam body. Therefore, β can be obtained through dynamic analysis. In this research, in order to obtain this parameter, a geometrical model of Masjed Soleiman Dam has been analyzed dynamically using seismographs of earthquakes that occurred in Manjil and Ghaen. The acceleration for these two earthquakes was reported to be 0.34g. Dam consultants used this value for the MDE of the Masjed Soleiman Dam site. Parameter β was obtained by assessing the way in which the maximum acceleration varied at different points on the height of the dam.

Next, the model was analyzed using the pseudo-static method and horizontal acceleration coefficients 0.1, 0.12, 0.14, 0.15, 0.16, 0.18, and 0.2. In this step, the safety factors corresponding to each of the stated coefficients were derived. To determine which acceleration coefficient to use to obtain results with the required precision as compared to those of the dynamic analysis, the effects of both methods on wedges of the dam body were compared at the same safety factor, which is a common factor in both methods and, in both, is derived using the same approach.

Initially, the safety factors of the wedges were calculated using the results of the dynamic and pseudo-static analyses. These factors are constant values for pseudo-static analysis and are time related for the dynamic analysis. Thus, it must be determined at what time the safety factor should be used as the dynamic safety factor.

In this research, the safety factor in a wedge corresponding to the seismograph that causes the allowable displacement in that wedge is assumed to be equal to one. Thus, available seismographs were scaled to peak acceleration values and, using them, the wedge displacement values were calculated. The safety factor changes were then calculated using the seismograph that caused the allowable displacement in the wedge. These safety factors were assumed to be equal to one and the dynamic safety factor for each wedge was determined by comparison of the results obtained from the original seismograph. After comparison of the dynamic and pseudo-static safety factors, the desired safety factor was determined. Finally, the distribution of the horizontal acceleration corresponding to the safety factor was compared with the linear distribution of horizontal acceleration proposed in this article and the values of β were determined.

Static, Pseudo-Static and Dynamic Analyses

Specifications of the Model

Masjed Soleiman Dam and power plant are located in Khuzestan province, 25.5km northeast tof the city of Masjed Soleiman and 26km downstream of

Shahid Abbaspour Dam on the Karoon River. Geologically, the dam foundation is located on Bakhtiari and Aghajari formations composed of stiff conglomerate with clay mid-layers.

In order to perform the static analyzes and, subsequently, the pseudo-static and dynamic analyses, all studies were done on a model of Masjed Soleiman Dam and a critical cross section was extracted based on the layout and sections presented in the technical layout plans of the dam body. The critical sections that were analyzed, including dam zones such as the core, filters, shell, transition zone and some parts of the alluvial foundation upstream and downstream have been modelled (Figure 1).

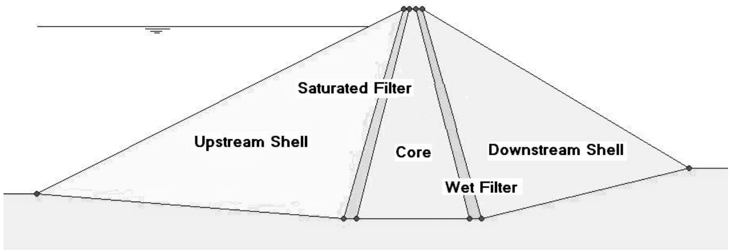

Fig. 1 Geometrical Model of Masjed Soleiman Dam

The model was simulated using a plane strain state with 15 node elements. The model height from foundation is 170m and its width at the crest is 15m. An effort was made to limit the number of elements while incorporating the actual geometric details of the dam into the model. To this end, the materials of the upstream and downstream shells, upstream and downstream filters and core have been separately included in the model.

The boundaries should be set far enough from the dam model that abnormalities resulting from wave reflection can be prevented in dynamic analyses. Thus, foundation boundaries were set so that the foundation depth was three times the height of the dam and the distance of the boundaries on each side were three times the width of the dam foundation. In addition, energy absorbing boundaries were used. In order to include the effect of a layer by layer analysis of the dam body, it was divided into eight layers. The reservoir water level was assumed to be 160m and the results were studied in a steady seepage state. In Figure 1, the dam zoning of the body and part of the foundation are shown.

In the static analysis, an elastoplastic behavioral model was used with Mohr-Columb criteria for the dam body material. Required parameters for static analysis and modified parameters for dynamic analysis are introduced in Tables 1 and 2. To select c and φ, it was assumed in the steady seepage analysis that there was enough time for complete drainage and for the material to exhibit drained behavior. For the dynamic analysis, the maximum shear modulus and Poisson ratio for materials used in the body and foundation of the dam were selected using the results of the cyclic triaxial tests, the amplification column and the values used by the dam designers. After doing the dynamic analysis, maximum values of shear modulus throughout the body and foundation of the dam were modified using the shear wave velocity in the surface layers obtained from geosiesmic tests and the experimental curves of shear wave velocity changes with height. To accommodate moody frequencies, Railey damping was used in the dynamic analyses.

To assess the stability and calculate the safety factors, sliding surfaces with high sliding potential that have been identified by the dam designer were selected. The locations of these surfaces are shown in Figure 2.

Table 1 Parameters Used in Static Analysis of Masjed Soleiman Dam (Davoodi, 2003)

Component	E(10^8N/m^2)					ψ deg	ϕ deg	C(10^5N/m$^{2)}$	υ	ρ(kg/m^2)
	148m	93m	43m	31m	12m					
Core	1.60	0.70	-	0.30	-	0	19	0.4	0.34	2200
Upstream shell	1.33	1.09	-	0.64	0.86	22	45	0	0.40	2350
Downstream shell	1.30	1.02	0.7	-	-	18	37	0	0.38	2200
Saturated filter	1.44	0.94	-	0.49	-	0	40	0	0.36	2350
Wet filter	1.55	1.06	-	0.70	-	0	40	0	0.36	2200

Table 2 Modified Material Parameters of Masjed Soleiman Dam with Constant Factors (Davoodi, 2003)

Component	E(10^8N/m^2)					ψ deg	ϕ deg	C(10^5N/m$^{2)}$	υ	ρ(kg/m^2)
	148m	93m	43m	31m	12m					
Core	4.21	3.85	-	2.23	-	0	19	0.40	0.45	2200
Upstream shell	3.15	2.99	-	2.35	-	22	45	0	0.40	2350
Downstream shell	5.80	5.40	3.85	-	0.88	18	37	0	0.40	2200
Saturated filter	1.82	1.71	-	1.34	-	0	40	0	0.40	2350
Wet filter	3.30	3.07	-	1.74	-	0	40	0	0.40	2200

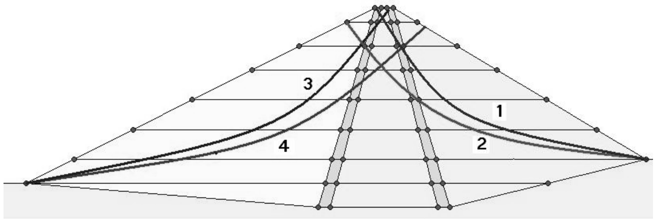

Fig. 2 Position of Failure Surfaces (Ahmadi, 2007)

Pseudo-Static Analysis

In the current research, the pseudo-static analyses of Masjed Soleiman Dam model were done using horizontal acceleration coefficient values of 0.1, 0.12, 0.14, 0.15, 0.16, 0.18 and 0.2 and their negative equivalents. For each positive/negative set, the minimum of the two safety factors obtained was selected as the safety factor for that set. The safety factors were determined by first dividing the sliding surface into vertical slices and selecting one point on the base of each sliding surface. The static and pseudo-static stresses of the selected points were determined. Next, the shear and normal stresses were determined in the direction of the tangent line of the center of the base of each slice using the Mohr circle. The formula for calculating the available shear stresses across the sliding surface is:

$$\tau f = c + \sigma_n \tan\varphi \qquad (3)$$

Finally, using the mobilized and available shear stresses calculated previously, the safety factor for the sliding surface was calculated using the following formula:

$$SF = \frac{\sum \tau_{fi} l_i}{\sum \tau_{ni} l_i} \qquad (4)$$

Where li is the length of slice base i in the direction of the sliding surface and τfi and τni are the mobilized and available shear stresses on the base of slice i in the direction of the sliding surface. The results for the sliding surface safety factor calculations are given in Table 3.

Table 3 Safety Factors of Slip Surfaces in Pseudo-Static Analyses

Slide No.	Seismic Coefficient Values				
	0.20	0.18	0.16	0.15	0.14
1	1.01	1.09	1.14	1.16	1.19
2	1.12	1.18	1.23	1.25	1.28
3	1.17	1.22	1.29	1.33	1.38
4	1.28	1.35	1.40	1.46	1.53

Dynamic Analysis

For dynamic analysis of the model, the records of the Manjil and Ghaen earthquakes applied to the bedrock as input for the dynamic analysis. The above records were scaled to a peak acceleration of 0.34g, the MDE reported by the designers for the Masjed Soleiman site (Figure 3).

The results of the dynamic analysis relevant to determination of the safety factors of the sliding surfaces are the variations in the horizontal, vertical and shear stresses during an earthquake. To determine the safety factors of the wedges during an earthquake, the safety factors were determined at specific points in time as was done for pseudo-static analyses. As a result, in the dynamic state, the safety factor changes with time instead of being a constant value as for pseudo-static safety factors.

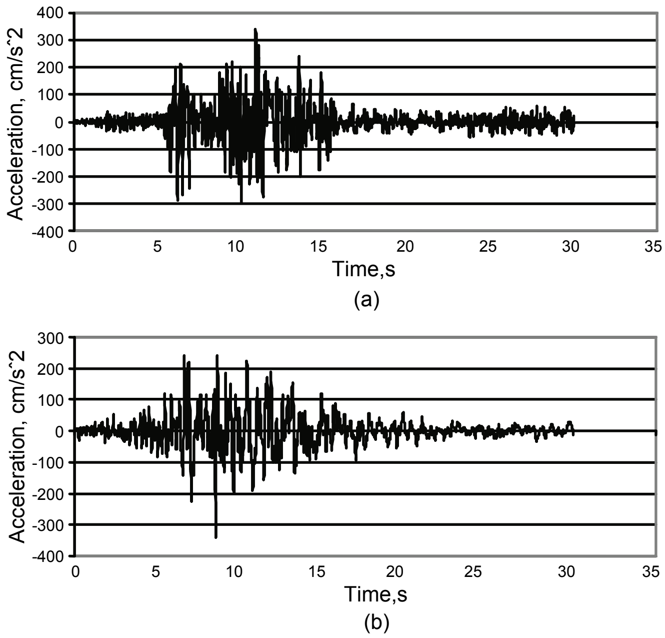

Fig. 3 Earthquake Records for (a) Manjil (b) Ghaen Scaled to 0.34g

After dynamic analysis of Masjed Soleiman Dam using the Manjil and Ghaen earthquake records, the safety factor for each wedge was determined using the same method that was used to determine the pseudo-static safety factor, except that for the calculation of shear strength, geotechnical dynamic parameters were used as follows (Das,1985):

$$c_{dyn} = 1.5c_u \qquad (5)$$

$$\varphi_{dyn} = \varphi_{static} - 2 \qquad (6)$$

For the dynamic state, the equation becomes:

$$SF(t) = \frac{\sum \tau_{fi}(t) l_i}{\sum \tau_{ni}(t) l_i} \qquad (7)$$

Safety factors changes with time for wedge no. 1, which is the most critical wedge are shown in Figure 4.

Based on the algorithm used, the safety factors obtained from the results of pseudo-static analysis should be compared with the dynamic safety factors. It must now be determined at what point in time should the dynamic safety factor be compared with the pseudo-static safety factor. The method used here was to relate the pseudo-static and dynamic safety factor changes to permanent displacement.

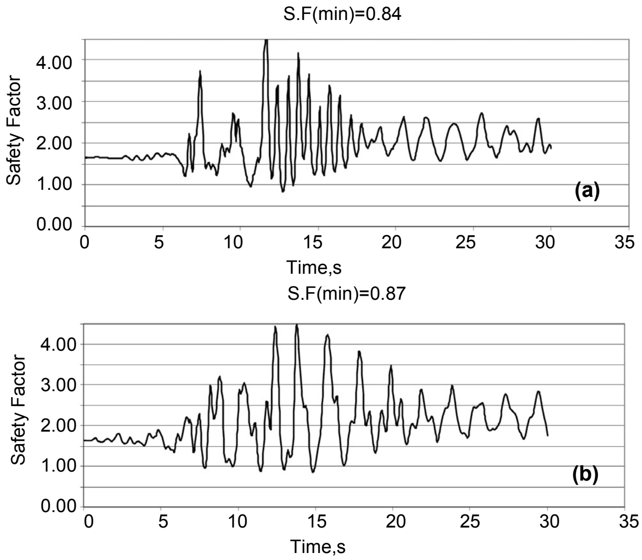

Fig. 4 Variations in Safety Factor in Wedge No. 1 during (a) Manjil Earthquake; (b) Ghaen Earthquake

Displacement limitation in pseudo-static analysis has been reported by Seed(1979) and Hynes-Griffin and Franklin(1984) as equivalent to 100cm or 15 to 30cm for embankments. It is clear that these limitations were obtained by analysis of earthquake statistics and the sections used. Thus, the limitations selected are dependent upon engineering judgment and may be relative. In this research, the intended displacement is assumed to be 30cm. Therefore, if an earthquake causes 30cm of displacement in a wedge, then variations in the safety factor in dynamic analysis are assumed to be one in pseudo-static analysis.

The seismographs used should be capable of causing a 30cm permanent displacement in the wedge. For this purpose, the seismographs were scaled to 0.2g, 0.25g, 0.3g, 0.4g, 0.45g and 0.5g and a dynamic analysis was performed for each wedge using each of the scaled seismographs. Then, permanent displacement was calculated using the mean acceleration of each wedge (Eq. 8) and the sliding block theory. A program developed using Matlab software (Mathworks, 2006) was used to calculate the permanent displacement. In this program, the time history of the mean acceleration and the failure acceleration, a_y, of the wedges was used as input. The program calculates permanent displacement of the wedge by integration of the mean acceleration curve and taking into account the failure acceleration values.

$$\overline{a}(t) = \frac{\sum a_i(t)A_i}{\sum A_i} \qquad (8)$$

where A_i is the area of variation of the wedge slices.

In Figures 5 and 6, mean acceleration changes and the results of the calculation of permanent displacement in wedge no. 1 are shown. These calculations are done for all wedges and the maximum acceleration values of the seismographs that lead to 30cm displacement in each wedge are presented in Table 4.

Next, variations of the safety factors for each wedge were calculated using the seismographs for which the values are presented in Table 4. Based on the

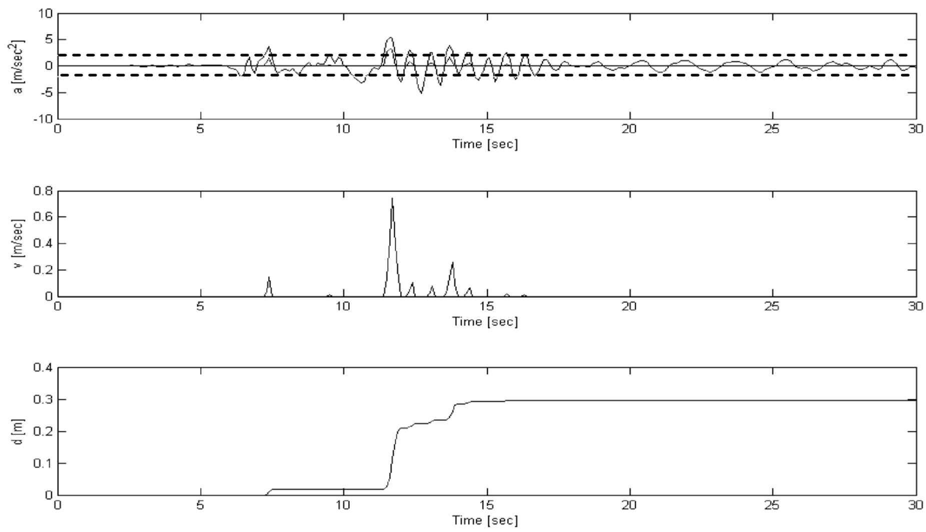

Fig. 5 Calculation of Permanent Displacement in Wedge no.1 using the Manjil Seismograph Scaled to 0.34g

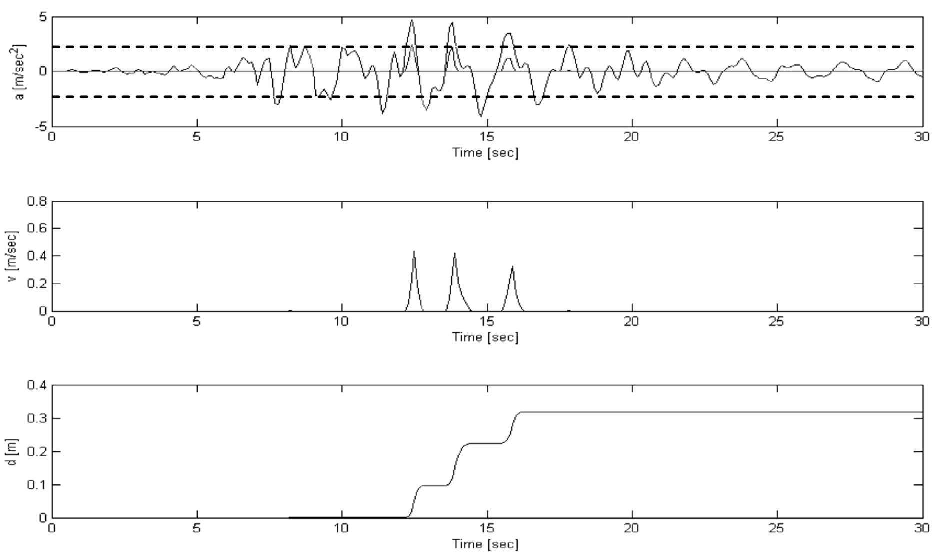

Fig. 6 Calculation of Permanent Displacement in Wedge No.1 using the Ghaen Seismograph Scaled to 0.41g

Table 4 Peak Acceleration Values Creating 30cm Displacements in One Wedge

Slide No.	Ghaen earthquake	Manjil earthquake
1	0.41g	0.43g
2	0.42g	0.45g
3	0.46g	0.50g
4	0.48g	0.50g

described assumptions, these safety factor changes were assumed to be equivalent to a pseudo-static safety factor of one. Figures 7 and 8 show the variations of the safety factors of the seismographs causing 30cm displacement in wedge no. 1 ($SF(t)_{30}$). These calculations were done for all wedges.

Calculation of Horizontal Acceleration Coefficient Parameters

Parameter β, which is indicative of acceleration amplification in dam height, is obtained directly from dynamic analysis results. Parameter α is obtained by comparing dynamic analysis and pseudo-static analysis results.

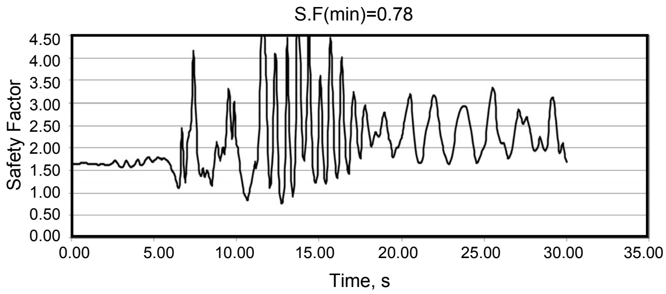

Fig. 8 Variations of Safety Factors for Wedge No. 1 in Ghaen Scaled with Peak Acceleration of 0.41

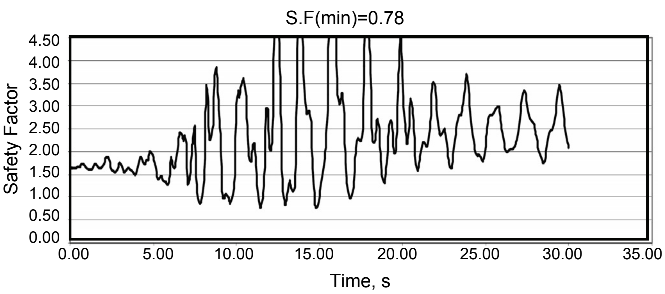

Fig. 8 Variations of Safety Factors for Wedge No. 1 in Manjil Scaled with Peak Acceleration of 0.43

Calculation of β

To calculate β, acceleration distribution by height should be defined. Note that the failure wedges expand to the width of the dam body. In addition to variations of acceleration by height, the way in which peak acceleration changes in relation to the width of the dam body at a constant height is important.

As shown in Figure 9, peak acceleration changes were determined at three constant elevations throughout the width of the dam body. A base point was selected on the central axis of the dam for each base height and variations in acceleration were determined horizontally to each base point.

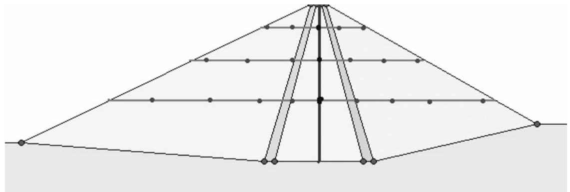

Fig. 9 Horizontal Distribution of Points at Three Constant Elevations

Figures10 and 11 show that the ratio of peak acceleration at each point to the peak acceleration in the dam axis increases at a specific height as the distance from the central axis of the dam increases. This increase is more tangible at higher elevations. The peak acceleration increases to a maximum of 12%. By reasonable approximation, the acceleration changes by height on the central axis of the dam can be used to calculate β.

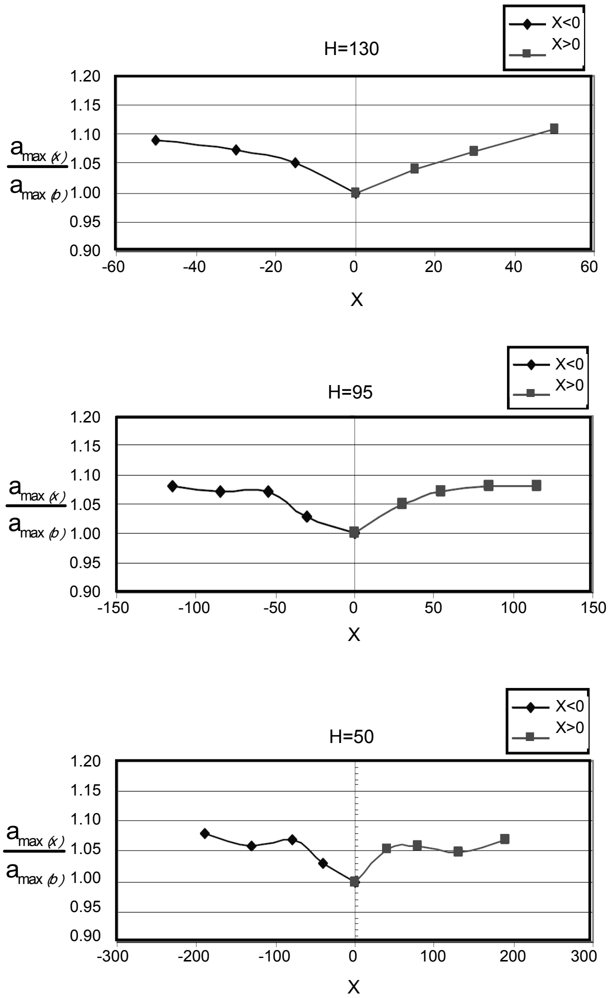

Fig. 10 Variations of Peak Acceleration across Dam width Relative to the Central Axis at Different Heights (Ghaen Earthquake)

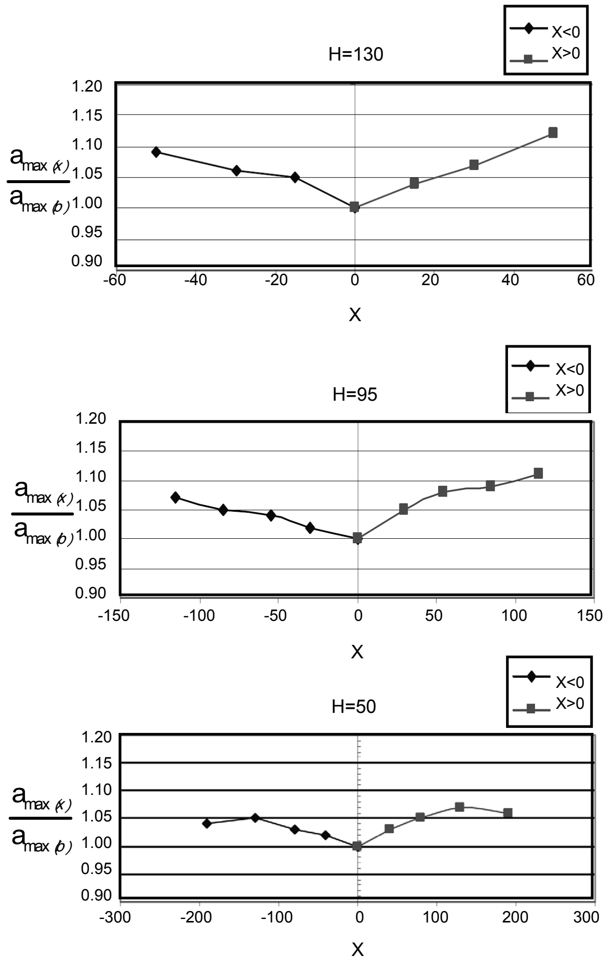

Fig. 11 Variations of Peak Acceleration across Dam width Relative to the Central Axis at Different Heights (Manjil Earthquake)

After plotting the variations in peak acceleration by dam height, assuming the linearity of these changes and fitting the best line passing through these points, it can be concluded that the average gradient of linear change for peak acceleration by height is 1.4 and the value of β can be assumed to be 0.4 (Figure 12).

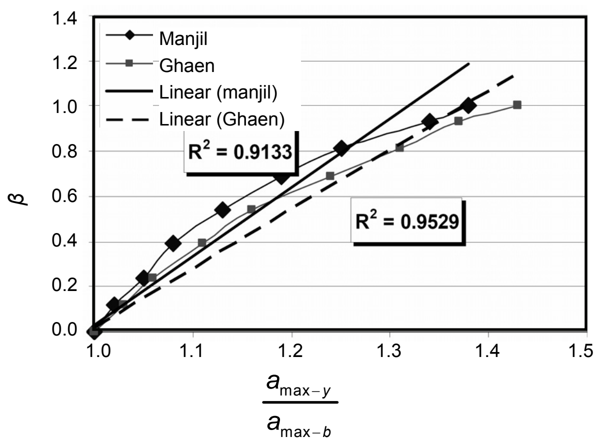

Fig. 12 Assumption of Linear Variation for Peak Acceleration by Height

Calculation of α

To convert dynamic safety factors to static safety factors in Eq. 9, λ is extracted and, by applying this factor to the dynamic safety factors resulting from the seismographs scaled to MDE, an equivalent safety factor can be obtained:

$$\lambda(\overline{f}(S.F(t)_{30})) = 1.0 \qquad (9)$$

Since the only times considered are when the dynamic safety factor is lower than the static state safety factor, the function *f* is applied to the values of the safety factors as they change over time. This function only extracts values that are less than the safety factor at t = 0. For example, variations in the safety factor in wedge no. 1, $f(SF(t)_{30})$, are shown in Figure 13.

Function $\overline{f}$ calculates the average of the safety factors at times when those factors are less than the static state safety factor. Therefore, at first, *f* considers variations in the safety factor (Figure 13) and then $\overline{f}$ calculates the average value of the safety factors less than that of static state.

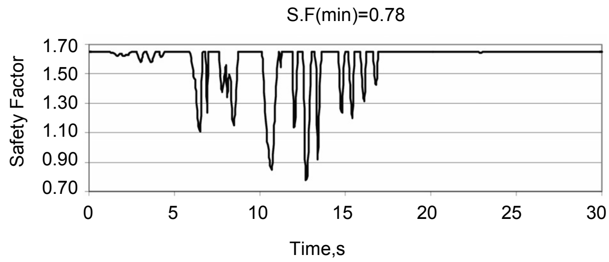

Fig. 13 Effect of Applying *f* to (SF(t)30) for Wedge No. 1 (Manjil Earthquake)

By obtaining $f(SF(t)_{30})$ for the four wedges and the Manjil and Ghaen earthquakes, the values of $\overline{f}$ corresponding to each state were calculated and the values of λ were obtained (Table5).

Finally, the equivalent pseudo-static safety factor for each wedge was calculated using Eq. 10:

$$SF_E = \lambda \overline{f} SF(t) \qquad (10)$$

where SF_E is the equivalent dynamic safety factor value which is a value comparable to a pseudo-static safety factor.

Table 5 Conversion Coefficients of Dynamic Safety Factors to Pseudo-Static Safety Factors.

Slide No.	*Ghaen earthquake*		*Manjil earthquake*	
	λ	$\overline{f}(SF(t)_{30})$	λ	$\overline{f}(SF(t)_{30})$
1	0.78	1.29	0.73	1.36
2	0.78	1.29	0.72	1.38
3	0.66	1.52	0.64	1.58
4	0.54	1.84	0.52	1.91

Next, by comparing the equivalent dynamic safety factors (Table 6) to the pseudo-static safety factors (Table 3) for each wedge, the seismic coefficient was obtained. Since the equivalent safety factors for each wedge have similar values for the two earthquakes, the average of these two values was considered to be the dynamic safety factor.

Table 6 Equivalent Dynamic Safety Factor Values for Wedges

Slide No.	Ghaen earthquake		Manjil earthquake	
	SF_E	$\overline{f}(SF(t))$	SF_E	$\overline{f}(SF(t))$
1	1.08	1.38	1.09	1.48
2	1.08	1.39	1.12	1.55
3	1.09	1.65	1.12	1.72
4	1.12	2.08	1.14	2.21

The pseudo-static safety factors closest to the average equivalent dynamic safety factors were selected (Table 7). Table 8 shows the α values for each wedge. The α for the most critical wedge (α = 0.44) is assumed to be equivalent to the α value for Masjed Soleiman Dam. Figure 14 shows the proposed distribution of horizontal acceleration coefficients by height for Masjed Soleiman Dam.

Table 7 Comparison of Average Equivalent Dynamic and Pseudo-Static Safety Factors and Horizontal Pseudo-Static Acceleration.

Slide No.	$(SF_E)_{ave}$	$SF_{Pseudostatic}$	K_h
1	1.085	1.09	0.18
2	1.100	1.12	0.20
3	1.110	1.17	0.20
4	1.130	1.33	0.20

Table 8 Values of α for Wedges

Slide No.	α
1	0.44
2	0.48
3	0.48
4	0.48

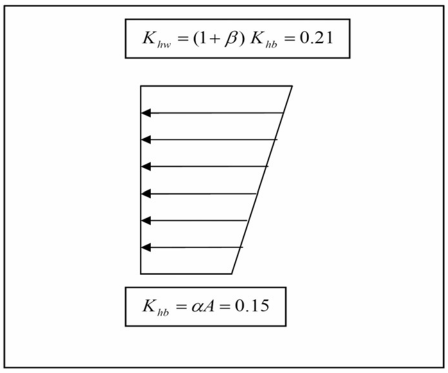

Fig. 14 Proposed Distribution of Horizontal Pseudo-Static Acceleration by Height for Masjed Soleiman Dam

Conclusion

A review of methods proposed by various researchers revealed that there is no general selection method for pseudo-static coefficients for earth dams that consider the effects of site seismicity and physical and geometrical characteristics simultaneously. Previous researchers and earth dam design manuals often present constant values for the pseudo-static coefficients regardless of site seismicity and the dynamic characteristics of a structure.

To evaluate the stability of earth dams, a new equation was presented herein to determine the pseudo-static coefficient. In this equation, variations of acceleration by height were considered to be linear and the gradient of this line related to soil stiffness, damping and the geometrical characteristics of the dam. Also, base acceleration value of the dam was determined based on the seismicity conditions of the region and site effects. The proposed equations are:

$$K_{hb} = \alpha A \qquad (11)$$

$$K_h(z) = K_{hb}\left(1+\beta z\right) \qquad (12)$$

The presented process to achieve real values for the pseudo-static coefficient was such that, by conducting a dynamic analysis, the effects of geometrical characteristics and material properties were determined in the variations of parameter β.

Based on the results of the analysis, it was shown that at a constant height, as the distance from the core center increases toward the sides, the ratio of peak acceleration at every point to the peak acceleration at the central dam axis increases. This increase is more tangible at higher elevations.

By comparing the pseudo-static and dynamic safety factors, the following equation for determining the pseudo-static coefficient for Masjed Soleiman Dam (α = 0.44, β = 0.4) was proposed.

$$K_{hb} = \alpha A = 0.15 \qquad (13)$$

$$K_{hw} = 1.40 K_{hb} = 0.21 \qquad (14)$$

Acknowledgement

This work was supported by a Tarbiat Moallem University grant. The authors wish to thank the Vice-Chancellor for Research at TMU for their scientific support this work.

References

Ahmadi, B., (2007): 'A study of pseudo-static coefficients for stability analysis of earth dams', *MS thesis*, Tarbiat Moallem University.

Das, BM., (1985): *Fundamentals of soil dynamics*, New York: Elsevier.

Davoodi, M., (2003): 'Evaluating dynamic characteristics of embankment dams using ambient and forced vibration tests', *PhD thesis*, International Institute of Earthquake Engineering and Seismology.

Hynes-Griffin, ME, and Franklin, AG., (1984): 'Rationalizing the seismic coefficient method. *US Army Corp of Engineers*, Waterways Experiment Station, Vicksburg, MS: paper GL-84-13.

IITK-GSDMA., (2005): *Guidelines for seismic design of earth dams and embankments*, Indian Institute of Technology Kanpur.

IS 1893 (Part 1), (2002): *Indian Standard Criteria for earthquake resistant design of structures*, New Delhi: Bureau of Indian Standards: 9. BIS.

Makdisi, FI, and Seed, HB.,(1978): 'A simplified procedure for estimating earthquake-induced deformation in dams and embankments', *J Geotech Eng*.,105(12), pp1427-1434.

Marcuson, WF., (1981): 'Moderator's report for session on earth dams and stability of slopes under dynamic loads', *Proceedings, International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*. St. Louis, Missouri, Vol. 3, p.1175.

Mathworks,(2006): MATLAB (Version 7.0.4) [Computer software], Natick: Mathworks.

Ozkan, YM.,(1998): 'A review of considerations on seismic safety of embankments and earth and rock-fill dams', *Soil dynamics and Earthquake Engineering*, 17, pp. 439–458.

Seed, HB., (1979): 'Considerations in the earthquake resistant design of earth dams", *Geotechnique,* 29, pp 215-263.

Terzaghi, K., (1950): 'Mechanism of landslides', Berkeley: *Geological Society of America*. pp. 83–123.