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ORIGINAL ARTICLE

Evaluation of Geometric Effect on the Pseudo-Static Seismic Coefficient in Embankment Dams

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ABSTRACT

Selection of appropriate seismic coefficients considering the geometry, stiffness and damping of materials is the foremost part of analysis in Pseudo-static approach. So Masjed Soleiman dam for a case study has been selected. Finite Element model of Masjed Soleiman dam has been constructed in GeoStudio-Geoslope software. Also in constructing of finite element model, has been used of Mohr-Coulomb failure criterion for body of dam. For analyses of finite element model, first a layer analysis has been carried out considering 12 layers in end of construction stage. Then, this analysis has been continued considering water table and weight of dam reservoir. 2 earthquake records in the far field condition have been applied horizontally to the bedrock as the input for dynamic analysis. In this study, to perform stability analysis and calculate the factor of safety, critical sliding surface on downstream that was reported by the consultant engineers have been considered. The semi empirical Newmark method for estimating permanent earthquake-related deformation of slopes is based on the sliding block framework. This conceptual framework approximates the potential sliding mass as a rigid body resting on a rigid sloping base. Assuming the allowable permanent deformations to be 300mm, a new perspective on dynamic factor of safety is proposed in this research. Also, in order to investigate the variations of pseudo-static acceleration coefficient along the height of dam, all analyses have been carried out in static, pseudo-static and dynamic conditions for the Masjed Soleiman dam assuming various geometrical properties. The results demonstrate a decrease in acceleration with increase in the height of dam and also an increase in the acceleration with steepening the slopes.

Keywords:Embankment dams, Pseudo-static method, Dynamic analysis, Masjed Soleiman dam

1. INTRODUCTION

Pseudo-static method, coined more than half a century ago by Terzaghi [1], is one of the oldest and perhaps simplest techniques for seismic stability analysis of embankment dams. This technique has been already employed for seismic assessment of soil slopes (e.g. Baker et al. [2] and Shukha et al. [3]), seismic analysis of rocky slopes (e.g. Said [4] and Li et al. [5]) and seismic evaluation of reinforced slopes (e.g. Ausilio et al. [6] and Nouri et al. [7]). Azad et al. [8] and Shekarian et al. [9] applied this technique in seismic design of retaining walls. Tokimatsu et al. [10] used it in a study on behavior of deep foundations during earthquakes. Recently, Park et al. [11] employed the concept for seismic evaluation of undergroundstructures. Hence this method has been so far of extensive interest for seismic evaluation of most earth structures such as embankment dams so that various schemes have been proposed to implement the pseudo-static analysis approach.

Seed and Martin [12] considered horizontal slices for estimation of acceleration and stresses with time for probable sliding surfaces in an earthquake. Investigating the distribution of acceleration and inertial forces applied to the probable sliding masses, they came up with a solution to determine the average earthquake coefficient.

Using the ground acceleration resonance spectrum curve in the body of dam and considering different values for the ratio of depth of wedge to the height of

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dam (y/h), Makdisi and Seed [13] calculated the ratio of (K_{max}/U_{max}) from finite element analysis applying the records of eight earthquakes. In this research, (K_{max}) is maximum average acceleration for a critical wedge extending to depth y and (U_{max}) is maximum acceleration in crest of dam. Finally, displacement of active wedge has been calculated.

In case of dams constructed from ductile materials that do not demonstrate significant excess pore pressure build-up or reduction in strength more than 15% during the earthquake, Seed [14] suggested the 0.1 and 0.15 pseudo-static coefficients for the earthquakes with magnitudes of 6.5 and 8.25, respectively. The minimum factor of safety in this method for stability of critical wedge was considered as 1.15.

Performing Newmark analyses for more than 350 acceleration records, Hynes-Griffin and Franklin [15] showed that embankment dams with a factor of safety greater than one with pseudo-static coefficient of about 50% peak ground acceleration (PGA), would demonstrate a deformation of about 1m. Also they showed that deformation of about 1m is not dangerous for this case.

As documented by the Japanese national committee of large dams, Yanagisawa [16] suggested the values ranging from 0.1 to 0.15 for earthquake coefficients based on the type of dam and the area where it's built.

Assuming the minimum factor of safety as 1, US Army [17] recommended using half the estimated acceleration for the bedrock in conjunction with 20% reduction in the strength of materials. It has also been recommended

Indian Institute of Technology Kanpur [18] has proposed the relation ($K_h=Z.I.S/3$) where (Z) is the seismicity coefficient of the region, (I) is the coefficient of importance and (S) is an empirical coefficient which shows the amount of resonance in the ground movements from the bedrock up to the toe of dam.

The proposed methods are of some flaws due to a few simplifications one of which is considering a constant seismic coefficient along the height of dam. The other one is neglecting the seismic conditions of the site, foundation and geometry of the dam and geotechnical properties of materials used in the body of dam in calculation of seismic coefficients. In this paper, a simple approach for calculation of pseudo-static seismic coefficient is presented which has improved some of the problems with previous techniques.

2. SUGGESTED EQUATIONS FOR CALCULATION OF PSEUDO-STATIC SEISMIC COEFFICIENT

Considering the seismic condition of the site, foundation and geometry of the dam in magnification of the base seismic coefficient and also the influence of geotechnical properties of materials used in the body of the dam, Ghanbari et al. [19] proposed a new technique to estimate the pseudo-static seismic coefficient. They considered a variable seismic coefficient along the height of dam as can be observed in equations 1 and 2.

$$K_{hb} = \alpha.A \tag{1}$$

$$K_h(Z) = K_{hb}(1+\beta.Z) \tag{2}$$

Pseudo-static seismic coefficient $K_h(Z)$ is a linear function increasing from the foundation to the crest of dam. (K_{hb}) is the base pseudo-static coefficient. The (A) parameter is the maximum design earthquake (MDE) with the returning period of 475 years. This parameter considers the seismic characteristics of the site. Also, considering the seismic condition, risk analyses and geological aspect of the site, magnitude of earthquake for the returning period of 475 years can be obtain. The (α) parameter is the ratio of design acceleration to the equal static acceleration which varies from 0.3 to 0.6 according to the site effects. The (β) parameter is a coefficient demonstrating the geometrical effects on the magnification of the base seismic coefficient and also the effects of geotechnical properties of materials used in the body of dam. It ranges usually from zero to 1.5. Parameter ($Z=y/h$) shows the coordinates of considered point along the height of dam. The center of coordination for the parameter (y) locates on the base of dam and (h) is also the height of dam. In order to improve the suggested method, Ghanbari et al. [19] studied the influence of embankment geometry on the seismic coefficient by performing static, pseudo-static, dynamic and Newmark analyses on the Masjed-Soleiman dam. But, this research has been done for 2 different acceleration records and 9 different geometries. This research has been extended all results that obtained in Ghanbari et al. [19] research.

3. STATIC, PSEUDO-STATIC AND DYNAMIC ANALYSES

The critical cross sections extracted from superposition of the technical plans of the Masjed Soleiman dam have been analyzed in this research. The Masjed Soleiman dam and its associated power plant have been constructed on the vicinity of Karoun River in the Khouzesstan province of Iran. The area is underlain by stiff Conglomerate with clayey seams. The main body of the dam has a volume of 13.5 million cubic meters. It is 177m in height (from the foundation) and 780m in width (on the foundation). Length and width of the crest are 480 and 15m, respectively. The excavation volume has been 1.8 million cubic meters. Location and Cross section of Masjed Soleiman dam presented in figure 1 and 2.

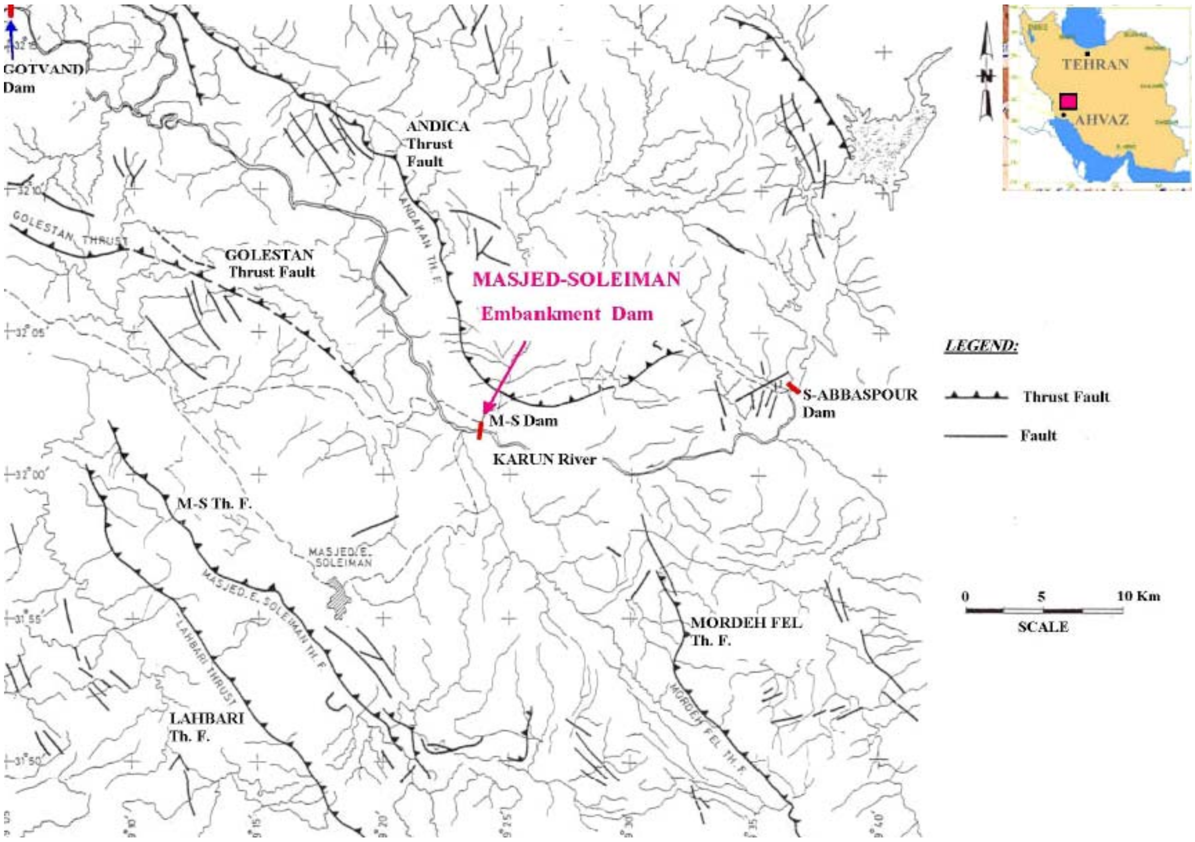


Figure 1.Location of Masjed Soleiman dam in Iran

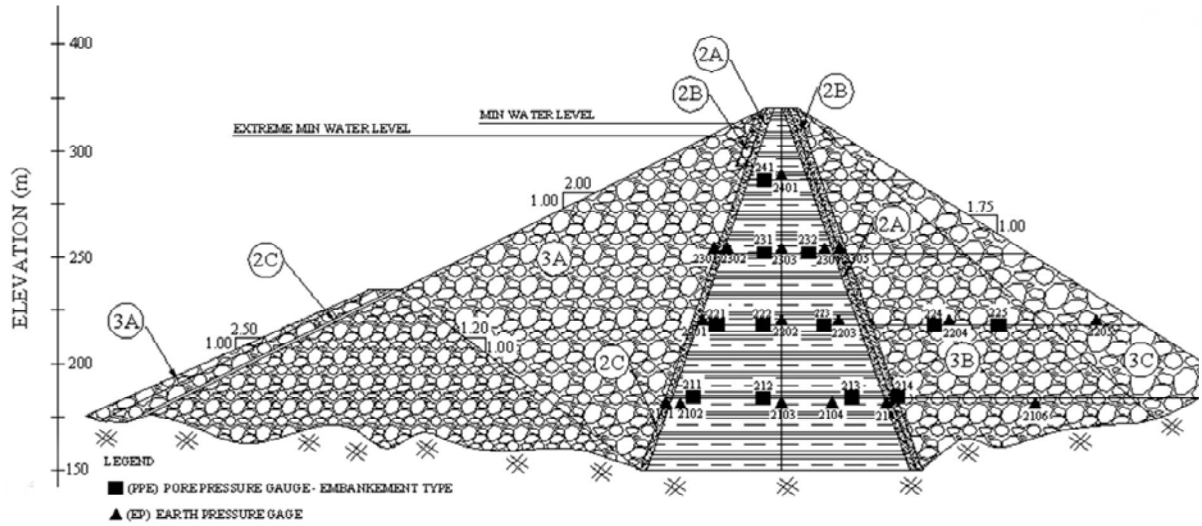
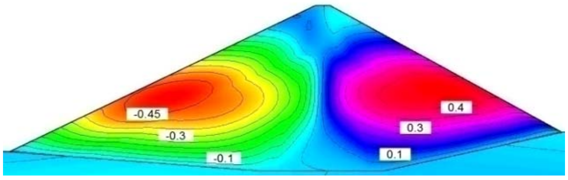


Figure 2.Cross section of Masjed Soleiman dam

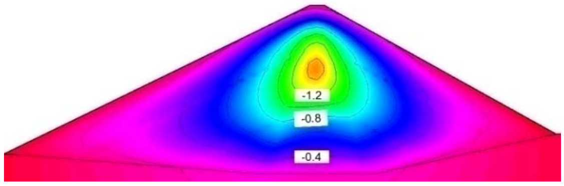
All analyses have been done with geostudio geoslope code. In this code, Sigma/w used for static analyses, Quake/w used for dynamic analyses and Slope/w used for Newmark analyses. Static analysis of the Masjed Soleiman dam has been carried out considering the Mohr-Coulomb failure criterion in the end of construction and steady seepage condition. At the end of the construction, the embankment dam is still undergoing internal consolidation under its own weight. Stage construction has been done after realizing insitu stress in the dam foundation. Then displacement of foundation has been considered zero. Number of layer is an important parameter in this step of analyses. Eisentein et al. [20] have showed that 10 layers is an adequate number of layers for making a good model. Elgamal et al. [21] proposed that 8 layers for modeling was the best assumption. Ultimately in this paper, 12 layers have been used for making of the model. Table 1 shows the properties of the used materials in the staged construction analysis. Obtained results in the final stage are illustrated in figure 3.

Table 1: The properties of materials in the staged construction analysis [22]

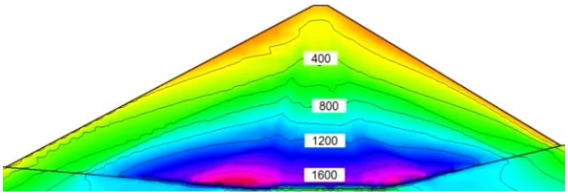
ZONE	*C (kpa)*	*Φ*	*ν*	*ρ (kg/m³)*	*ψ*	*E * (10^5 kPa)*				
						12m	*31m*	*43m*	*93m*	*148m*
Core	*50*	*10*	*0.34*	*2050*	*0*	*-*	*0.3*	*-*	*0.7*	*1.6*
Upstream Shell	*0*	*45*	*0.4*	*2350*	*22*	*0.86*	*0.64*	*-*	*1.09*	*1.33*
Down Stream Shell	*0*	*37*	*0.38*	*2200*	*18*	*-*	*-*	*0.7*	*1.02*	*1.3*
Saturated Filter	*0*	*40*	*0.36*	*2350*	*0*	*-*	*0.49*	*-*	*0.94*	*1.44*
Wet Filter	*0*	*40*	*0.36*	*2200*	*0*	*-*	*0.7*	*-*	*1.06*	*1.55*
Foundation	*700*	*30*	*0.3*	*2500*	*-*			*3.8722*		



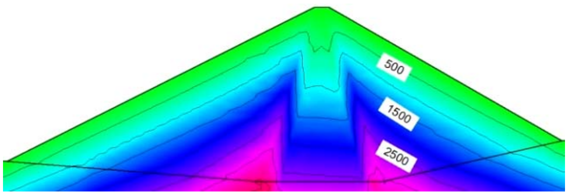
Horizontal displacement (meter)



Vertical displacement (meter)



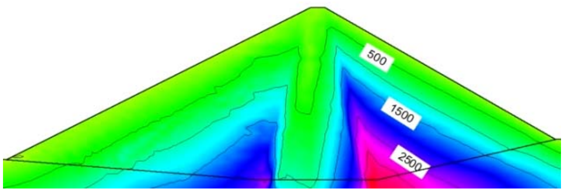
Horizontal effective stress (kPa)



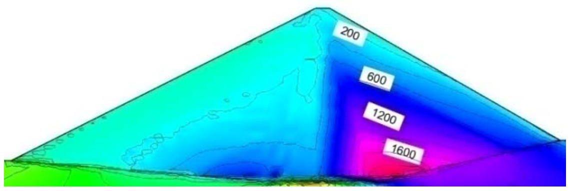
Vertical effective stress (kPa)

Figure 3: Obtained contours for various parameters from the final stage of construction

Steady seepage comes up after of the constant flow of water is maintained. In this condition, effective stresses and pore water pressures remain constant in their limiting values. Properties of the used materials in the steady seepage condition are same with layer analyses, but only Cohesion and friction angle have been changed to 40kPa and 19 degrees. All Properties of the used materials for 2 stages have been extracted of consulting engineering reports that mentioned in Davoodi [22]. Figure 4 demonstrates the obtained results from steady state seepage analyses.



Vertical effective stress (kPa)



Horizontal effective stress (kPa)

Figure 4. Various contours obtained in the steady state seepage stage

To perform stability analysis and calculate the factor of safety in the steady seepage condition, critical sliding surface reported by the consultant engineers has been considered. The location of this surface is depicted in figure 5.

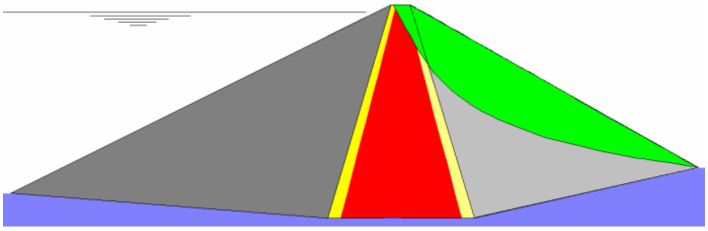


Figure 5. Location of the analyzed sliding surface

Using the horizontal acceleration coefficients of 0.1, 0.12, 0.14, 0.16, 0.18 and 0.2, stability analyses in static and pseudo-static conditions have been carried out for the critical failure surface of the Masjed Soleiman dam. Obtained results are summarized in table 2.

Table 2: Safety factors obtained from static and pseudo-static analyses

Seismic Coefficient Values	*0*	*0.1*	*0.12*	*0.14*	*0.16*	*0.18*	*0.2*
Safety Factors	***1.62***	***1.37***	***1.34***	***1.3***	***1.26***	***1.23***	***1.19***

The earthquake records of Kocaeli-1999 and Northridge-1994 in the far field condition have been applied horizontally to the bedrock as the input for dynamic analysis. Before analyzing the earthquake records, in all the records, the base line has been corrected and the band pass filter has been used. Also Earthquake records that are used for analyzing should be compatible with site conditions. The earthquake records have been scaled 0.34g based on consulting engineering report. Properties of the employed acceleration records are presented in table 3 and figure 6.

Table 3: Properties of the applied earthquake records in dynamic analyses [24]

Record	*Year*	*Magnitude*	*Epicentral Distance (km)*	*PGA (g)*	*PGV (cm/s)*	*PGD (cm)*
Kocaeli	***1999***	***7.51***	***209***	***0.0353***	***3.79***	***1.49***
Northridge	***1994***	***6.69***	***90***	***0.0645***	***4.44***	***0.73***

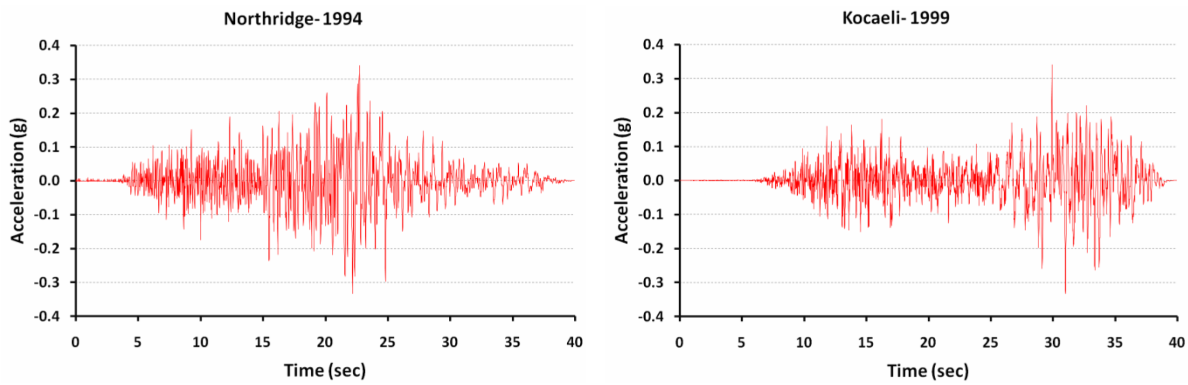


Figure 6. Time history of the far field earthquake records used in this research

Dynamic properties for the body of dam, core materials, shell and filters have been extracted from the reports presented by the consultant of the project as can be observed in table 4 and figure 7.Then, Dynamic analyses have been performed on these models. Equivalent linear method is used for dynamic analyses. This method is a simple and well known method for modeling non-linear and hysteretic behavior of materials. Also Geostudio Geoslope Code based on finite element method has been developed. Also for the accuracy of wave propagation in finite element model, has been used of Kuhlemeyer and Lysmer [24] method. Kuhlemeyer and Lysmer [24] showed that the wavelength (λ) determines the accuracy for wave propagation problems. They found that the length of the element must be less than (λ/10). In this research all element have been controlled to satisfy this criteria.

Table 4: Material properties used in the dynamic analyses [22]

ZONE	*C (kpa)*	*φ*	*ν*	*γ (kg/m³)*	*Ψ*	*E * (10⁶ kPa)*				
						12m	*31m*	*43m*	*93m*	*148m*
Core	*40*	*19*	*0.45*	*2200*	*0*	*-*	*2.23*	*-*	*3.85*	*4.214*
Upstream Shell	*0*	*45*	*0.4*	*2350*	*22*	*-*	*2.35*	*-*	*2.99*	*3.15*
Down Stream Shell	*0*	*37*	*0.4*	*2200*	*18*	*0.88*	*-*	*3.85*	*5.4*	*5.8*
Saturated Filter	*0*	*40*	*0.4*	*2350*	*0*	*-*	*1.34*	*-*	*1.71*	*1.82*
Wet Filter	*0*	*40*	*0.4*	*2200*	*0*	*-*	*1.74*	*-*	*3.07*	*3.3*
Foundation	*700*	*30*	*0.3*	*2500*	*-*			*10.92*		

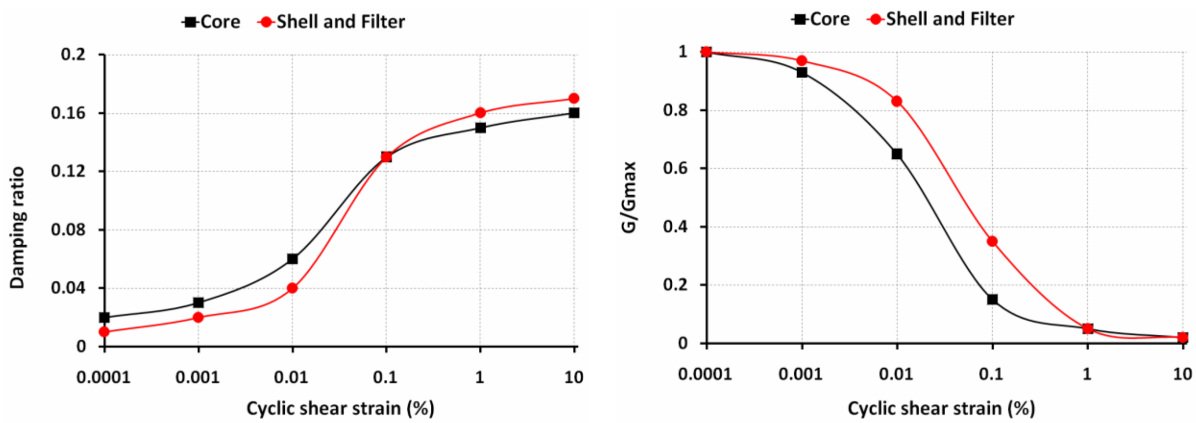


Figure 7. Dynamic properties of materials used in modeling [22]

4. CALCULATION OF PARAMETER (β)

The β parameter has been obtained based on the distribution of acceleration along the height of dam. For this purpose, two acceleration records namely the Northridge-1994 and Kocaeli-1999 have been used. Considering a base point located on the foundation and referring the central axis of dam at each elevation, changes in acceleration along the height of dam have been investigated. Eventually the effect of change in the height and slope of dam on the (β) parameter has been investigated. In order to achieve this goal, 8 other geometries, in addition to the number one which was the main model, have also been considered as noted in table 5. The maximum recorded accelerations in the middle axis of embankment dam in temporal domain are demonstrated in figures 8 and 9.

Table 5: Parameters related to the studied geometries

NO	*Height (m)*	*Upstream Slope*	*Downstream Slope*
1	*170*	*1V:2H*	*1V:1.75H*
2	*170*	*1V:2.4H*	*1V:2.15H*
3	*170*	*1V:2.2H*	*1V:1.95H*
4	*170*	*1V:1.8H*	*1V:1.55H*
5	*170*	*1V:1.6H*	*1V:1.35H*
6	*250*	*1V:2H*	*1V:1.7H*
7	*210*	*1V:2H*	*1V:1.75*
8	*130*	*1V:2H*	*1V:1.75*
9	*90*	*1V:2H*	*1V:1.75*

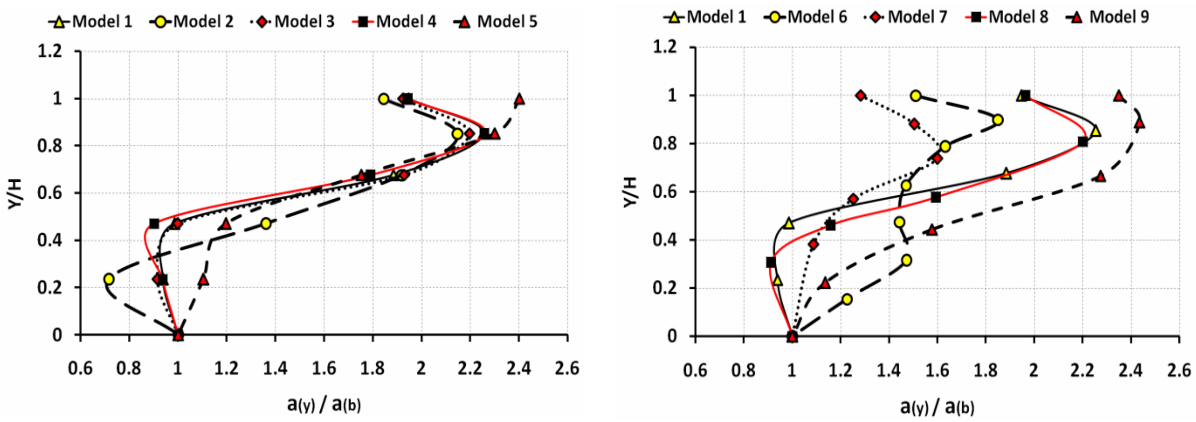


Figure 8. Comparison of the maximum accelerations for different models with applying Northridge-1994 earthquake records

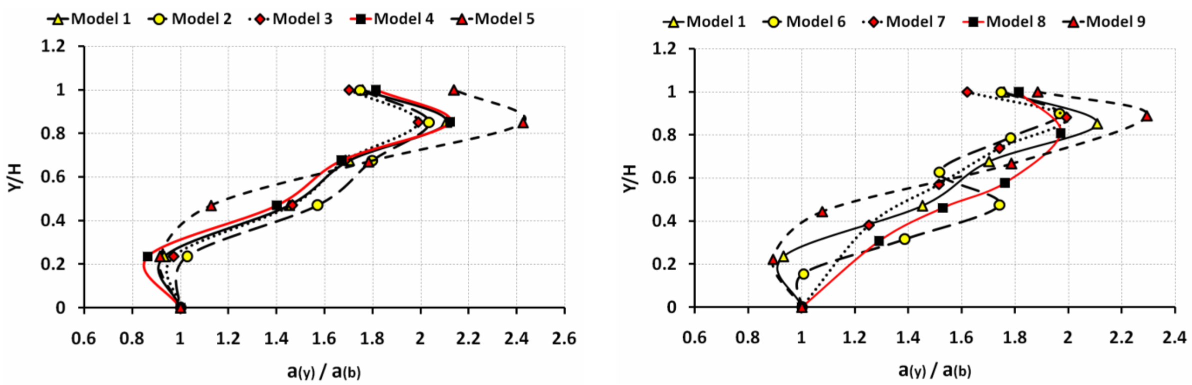


Figure 9. Comparison of the maximum acceleration for different models with applying Kocaeli-1999 earthquake records

Variations of β with elevation and slope have been depicted in figures 10 and 11, respectively. The horizontal axis in figure 11 is proposed as a two-row axis where upstream and downstream slopes are demonstrated on the upper and lower axes, respectively.

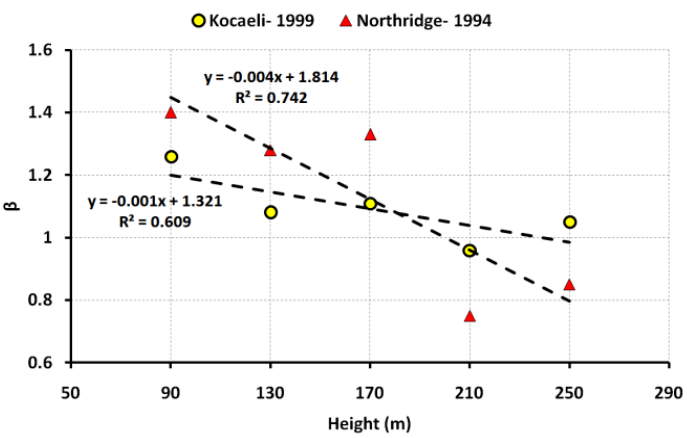


Figure 10. Variation of β parameter along the height of dam

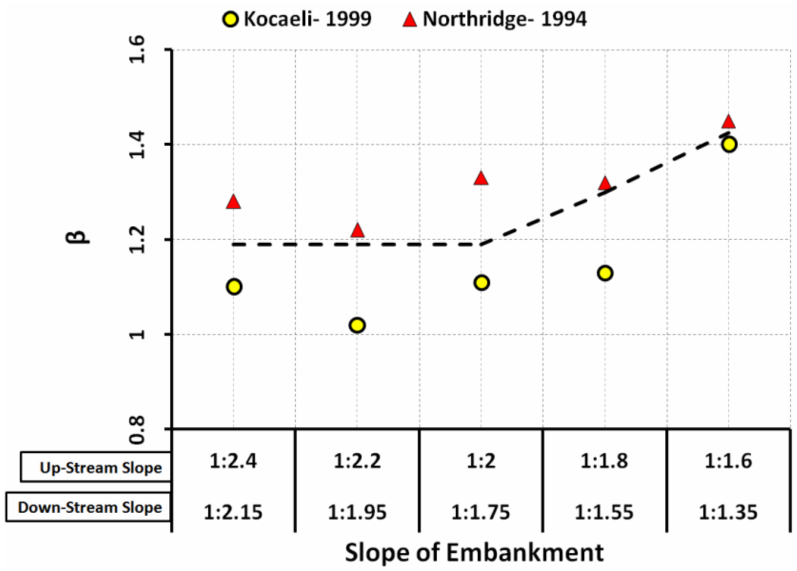


Figure 11. Suggested β parameter for various slope

5. CALCULATION OF (α)

Performing dynamic and Newmark analyses, the parameter α has been estimated. This way, changes in the factor of safety by time have been obtained from Newmark analyses. Finally, permanent deformations have been calculated at the moments that the resultant of initial static forces and inertial time-dependant ones exceeded the shearing resistance. Since the maximum base acceleration in the site has been 0.34 times the ground acceleration (i.e. 9.806 m/s^2), this maximum value has been used in dynamic and Newmark analyses. Variations of safety factor in the critical wedge have then been obtained for 2 acceleration records as demonstrated in figure 12.

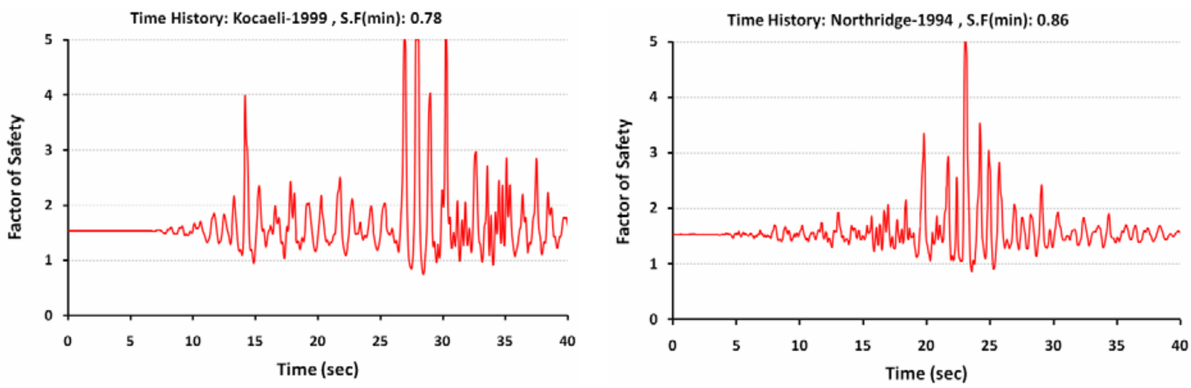


Figure 12. Variations of the safety factor for the considered wedge after applying the 2 acceleration records

The factor of safety resulted from pseudo-static analysis has been compared with the dynamic factor of safety. For the purpose of comparison, permanent deformations have been considered as the main criterion. Different researchers have employed different values for the permanent deformations. For instance, Makdisi and Seed [13] assumed 1m permanent deformation as the basis of their suggested seismic coefficients. Kavazanjian et al. [25] considered the permanent deformation of 1m as a criterion equivalent to the safety factor of 1 in their presented pseudo-static analysis. Bray [26] proposed the allowable permanent deformation in the critical wedge of embankment ranging from 150 to 300mm. It's obvious that the mentioned limitations are put based on the performed analyses and statistical study of earthquakes in considered sections.

In the suggested method by Ghanbari et al. [19], allowable permanent deformation for critical wedge has been considered as 300mm and thus the variations of safety factor in dynamic analysis leading to 300mm deformation in a wedge were assumed equivalent to the safety factor of one in pseudo-static analysis. Hence the maximum applied acceleration has to be selected so that by applying that accelerometer to the model, the permanent deformations of the wedge is equal to 300mm as suggested by Bray [26]. In order to achieve this goal, the applied acceleration records in dynamic analyses have been scaled to the maximum base accelerations of 0.3, 0.4, 0.45, 0.5 and 0.6 times the gravitational acceleration and then dynamic analysis has been conducted with 2 acceleration records. Subsequently, Newmark analysis in the critical wedge with different base maximum accelerations has been performed. Using the Newmark analysis, average applied acceleration on the critical wedge was calculated. Integrating the average acceleration, average velocity and consequently permanent deformations occurred in the critical wedge have been obtained.

Table 6 demonstrates the base maximum accelerations leading to 300mm displacements and figure 13 shows the procedure of obtaining the permanent deformations of 300mm in critical wedge.

Table 6: Base Maximum accelerations leading to 300mm deformation

Time history	*Base maximum acceleration (g)*
Northridge- 1994	*0.45*
Kocaeli-1999	*0.43*

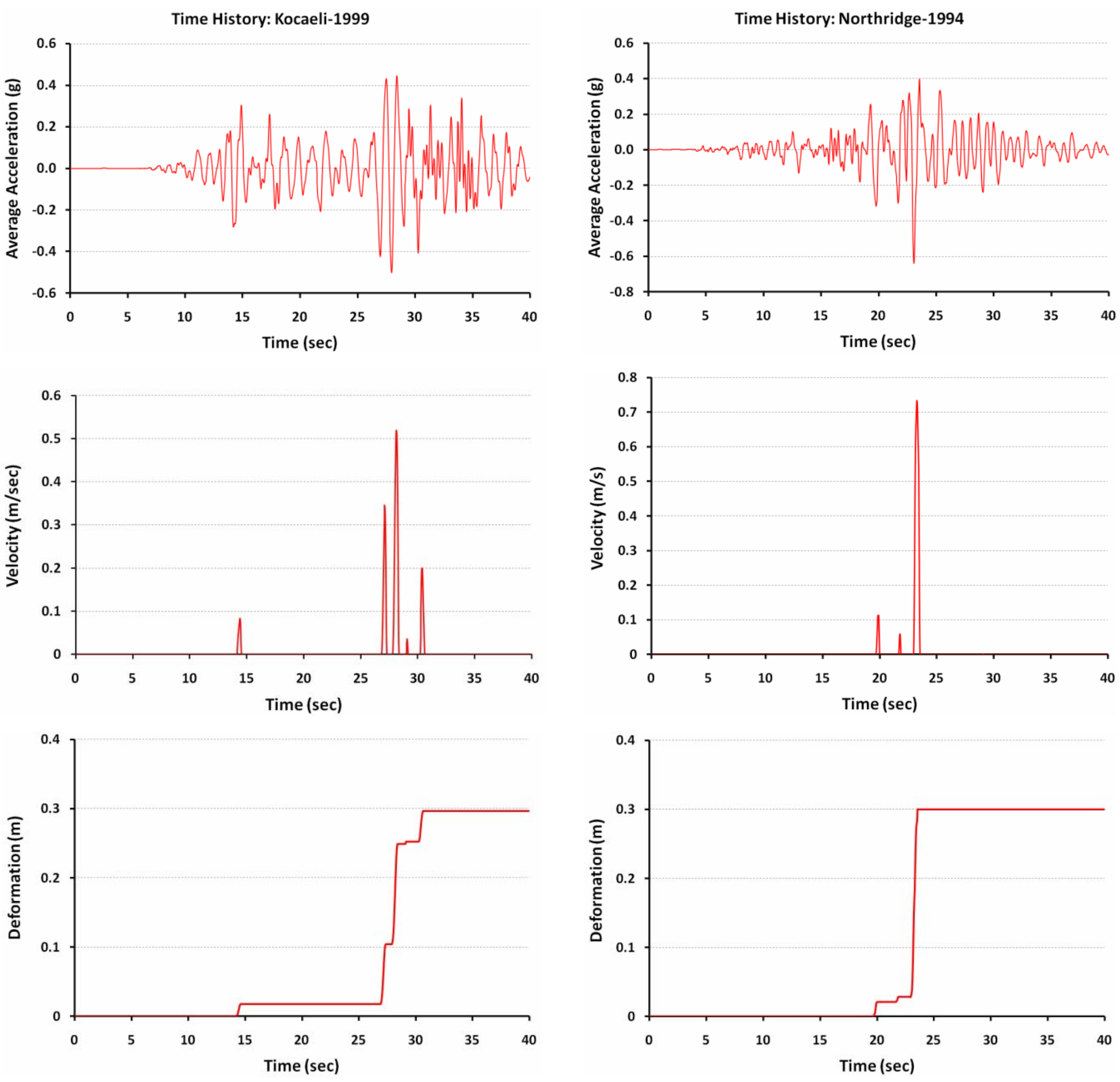


Figure 13. Calculation of permanent deformations in the critical wedge

After obtaining the required deformations, factor of safety has been calculated in a temporal domain for the base maximum acceleration leading to the 300mm deformation as illustrated in figure 14.

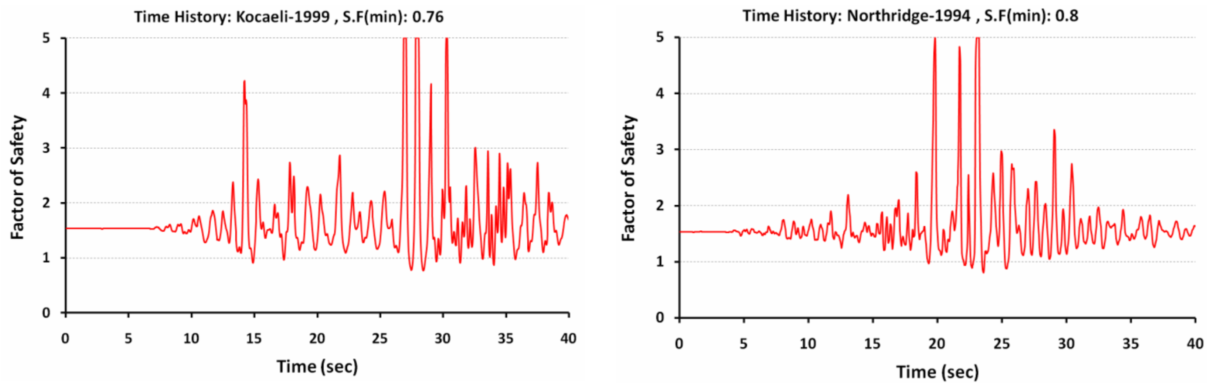


Figure 14. Variations of safety factor in critical wedge with the maximum acceleration

Also equation (3) has been used to convert the dynamic factor of safety to the equivalent pseudo-static one:

$$\lambda(\bar{f}(S.F(t)_{300}))=1 \quad (3)$$

In above equation $S.F(t)_{300}$ assumes the variations of safety factor in the critical wedge caused by an earthquake yielding 300mm deformation in the considered wedge. Variations of dynamic safety factor in moments at which the values less than the static safety factor have been considered. Therefore the function (f) has been applied for considering the values less than the static safety factor. The function ($\bar{f}$) calculates the average safety factors less than static condition in the whole temporal domain for the critical wedge applying two earthquake records. The (λ) value is a coefficient that has been calculated by the equation 3. The obtained results are demonstrated in table 7 and figure 15.

Table 7: Coefficients used to convert the dynamic factor of safety to the pseudo-static one

Time History	$\bar{f}(S.F(t))$	λ
Northridge-1994	1.464	0.68
Kocaeli-1999	1.429	0.7

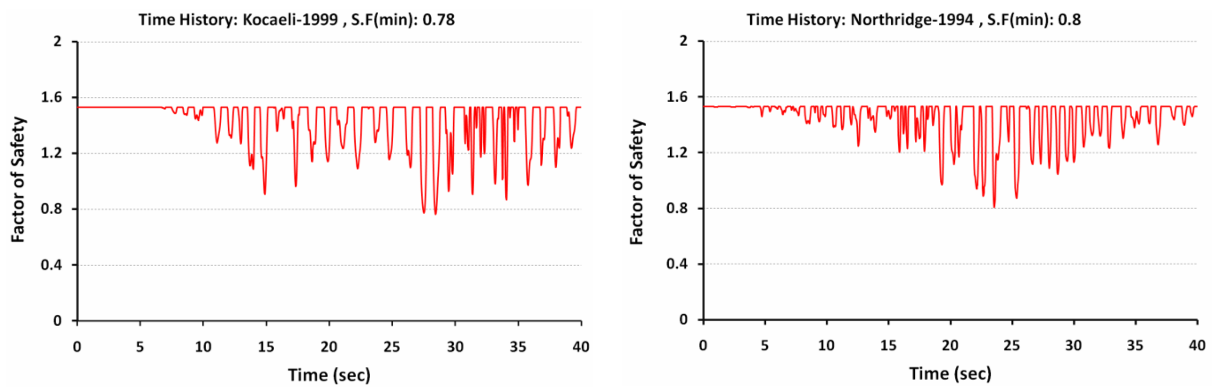


Figure 15: Effect f function on the equal safety factor

In the next stage, by applying the (λ) value on the average safety factor in the temporal domain for the Maximum DesignEarthquake, the equivalent pseudo-static safety factor has been calculated by equation 4.

$$S.F_E = \lambda.\bar{f}(S.F(t)) \quad (4)$$

($S.F_E$) is the equivalent pseudo-static factor of safety. The values of equivalent pseudo-static safety factor in thecritical wedge are summarized in table 8.Comparing the pseudo-static factor of safety with the obtained factor of safety from dynamic analyses; seismic coefficient leading to the desired safety factor has been obtained. Table 9 shows the obtained values.

Also since the equivalent safety factors for the critical wedge for two earthquakes records i.e. Northridge-1994 and Kocaeli-1999 have been close together, the average of these two values has been considered as the dynamic factor of safety. Eventually from the equilibrium of wedge in horizontal direction and using the previous studies the parameter (α) has been estimated as 0.4.

6. COMPARISON BETWEEN RESULTS

The selection of a seismic coefficient was based on judgment and experience of slope behavior during past earthquakes, and these coefficients were embodied in seismic design codes. Japanese Code [26] has been used for selection of suitable seismic coefficient. In this method seismic coefficient has been obtained from equation 5 and 6.

$$0 \prec \frac{y}{h} \le 0.4 \qquad K_h = K_f \times (2.5 - 1.85 \times \frac{y}{h}) \qquad (5)$$

$$0.4 \prec \frac{y}{h} \le 1 \qquad K_h = K_f \times (2 - 0.6 \times \frac{y}{h}) \qquad (6)$$

In these equations, (h) is height of dam, (y) is height of critical wedge, (k_f) is seismic coefficient for different zone that presented in table 10.

The Makdisi and Seed [13] simplified seismic displacement method is one of the most significant contributions to geotechnical earthquake engineering over the past few decades. But as they recommended, their design curves should be updated as the profession advances. Moreover, the important earthquake ground motion at a site is characterized by the PGA at the crest of the slope and earthquake magnitude.

In 1984 the regions of different seismic potential were identified on the basis of past earthquakes and the regional tectonic features, which was incorporated in zoned map and published in 1984 (BIS-1893, 1984). In 1988, Indian standard [27] suggested that horizontal acceleration factor must be obtained from equation 7 to stable critical wedge.

$$\alpha_y = (2.5 - 1.5 \frac{y}{h}) \times \alpha_h \qquad (7)$$

In this equation (h) is height of dam, (y) height of critical wedge, (α_h) is factor of horizontal acceleration that can be obtain from zoned map that between 0.03 to 0.24 has been changed.

In order to compare the proposed method by Ghanbari et al. [19] with other ones and considering the obtained results from previously calculated parameters, figure 16 has been plotted.

Table 8: The values of equivalent pseudo-static safety factor in the critical wedge

Time History	$S.F_E$	$\bar{f}(S.F(t))$
Northridge-1994	*1*	*1.46*
Kocaeli-1999	*1.1*	*1.43*

Table 9: Dynamic and pseudo-static factors of safety

$S.F_E$	K_h	$S.F_{Pseudo\ Staic}$
1.05	*0.2*	*1.19*

Table 10: seismic coefficient for deferent zone in Japan

Zone dangerous	k_f
High	*0.18*
medium	*0.16*
low	*0.13*

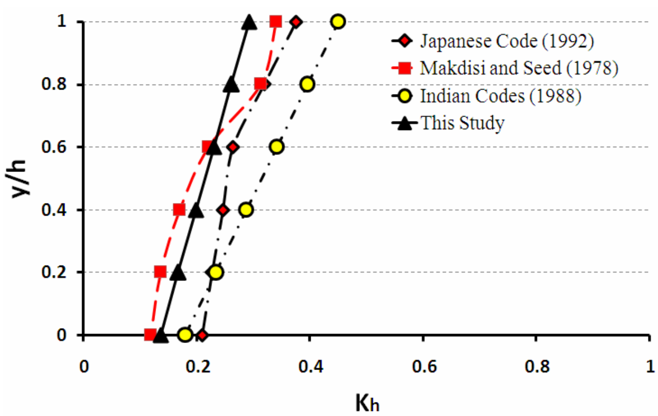


Figure 16: Comparison of obtained results with those reported in other references

7. CONCLUSION

Proposed methods by previous researchers for estimating the seismic pseudo-static coefficient in embankment dams are not of high precision due to some simplifications such as not considering the geometrical properties and location of the dam. Thus using the FEM analyses and applying a new method, the effect of geometry of dam on the value of pseudo-static coefficient was investigated in present research. The following results are concluded:

- The value of (β) increased by steepening the slope of dam. For the slopes less than 1V:2H its increasing trend was stopped and almost its value has been constant for all the slopes less than 1V:2H.
- By increase in the height of dam, (β) decreased and thus the increasing rate of seismic coefficient dropped.
- The acceleration increased up to about 80% of the height of dam and in this zone the linear trend for variations of acceleration could be accepted. However in the upper part of the dam around the crest a significant decrease in the acceleration of the body was observed.
- The pseudo-static method is a simple and powerful solution for seismic analysis of embankment dams, if improved and optimized for reliable calculation of safety factor.

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