A New Approach to Evaluate Seismic Stability of Asphaltic Core Rockfill Dams

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Abstract

Construction of asphaltic core dams is a relatively novel method especially in Iran. Iran is located in a region with high seismicity risk. Therefore, many researchers have focused on the behavior of such types of dams under earthquake loading. In this research, the behavior of asphaltic core rockfill dams (ACRD) has been studied under earthquake loading using nonlinear dynamic analysis method and a new method is presented to assess seismic stability of these types of dams in earthquake conditions. Based on nonlinear dynamic analysis, the current study attempts to provide an appropriate criterion for predicting the behavior of earth and rockfill dams considering real behavior of materials together with actual records of earthquake loading. In this method, the maximum acceleration of the earthquake record (PGA) increases until instability conditions. Finally, a new

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criterion is presented for evaluating seismic safety of ACRDs via demonstrating curves of the crest's permanent settlement and maximum shear strain against maximum earthquake acceleration. Results of the proposed criteria can assist designers of asphaltic core dams to predict dam stability during earthquake event.

KeyWords: Dam, Asphaltic Core, Dynamic Analysis, Crest Settlement, Shear Strain, Safety Evaluation.

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Introduction

The process of selection of different types of dams consist of technical and economical aspects. In some cases the rockfill dam option with asphaltic core is preferred considering different conditions such as location and characteristics of site, limitations in borrow sources, execution operations, etc. There is an increase in application of rockfill dams with asphaltic core because of their numerous advantages, including abundance of bituminous and asphaltic materials, decrease in body volume compared to the option of rockfill dam with clay core, less executive dependence on air conditions, simplicity of design and execution, not having the problem of providing material with low permeability such as clay, decrease in execution time, asphalt's significant characteristic of self healing specially in conditions of asymmetric settlements and during earthquake occurrence, etc. On the other hand, as this method is new,

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there are disadvantages such as insufficient experience of contractors and also the required equipments. Moreover, more investigation is required on the behavior of these dams in different conditions especially during earthquake.

Since many dams are built or being built in seismic regions, a safe design against earthquake is of great importance. A careful study of seismic stability of earth and rockfill dams is one of the complicated problems in geotechnical field. Factors such as variety in dynamic properties of dam body and diversity in material and thickness which can take a part in propagation, attenuation, and amplification of waves, existence of active fault near dam body, earthquake characteristics such as distance of epicenter to dam site, intensity and period, type and direction of the waves reaching the dam, and frequency content have important role in dynamic response of dams.

In the current research, initially, the existing methods and criteria related to seismic evaluation of dams are studied and then a new method is presented for safety evaluation of ACRDs in earthquake condition based on results of nonlinear dynamic analyses. The suggested method has the advantage of considering crest settlement and maximum shear strain while calculating the safety factor of slope stability. In addition, it is not necessary to assume a virtual value for each of the two mentioned parameters at beginning of analysis.

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Review of existing Methods

In general, methods of dynamic analysis of earth dams can be divided in three categories:

a) Pseudo-static methods;

b) Equivalent linear methods or the methods based on analysis of Newmark sliding block;

c) Methods of nonlinear dynamic analysis using numerical methods of finite elements or finite differences.

The critical components in displacement seismic analysis include ground motion, dynamic resistance of structure, and probable dynamic response of the sliding mass. Newmark (1965) sliding block method, which is extensively used or is utilized as a base for other techniques, covers only a part of dynamic shape changes caused by shear stresses while it does not include ground displacement caused by volume compression. Duncan (1996) found that consistent and reasonable estimates of static factor of safety (FS) of slopes are calculated if a slope stability method satisfies all three conditions of equilibrium. Methods by Spencer, Janbo, and Morgenstern-Price belong to this category. Most programs allow a horizontal coefficient (K_h) in equilibrium equations for pseudo-static analysis. Bray et al. (1998) presented relationships for calculation of K_y as a function of slope geometry, weight, and strength. Studies of researchers (e.g. Bray and Rathje, 1998) have indicated that seismic displacement also depends on the dynamic response characteristics of the potential sliding mass.

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With all other factors held constant, seismic displacements increase when the sliding mass is near resonance compared to that calculated for very stiff or very flexible slopes (e.g. Kramer and Smith, 1997; Rathje and Bray, 2000; Wartman et al., 2003). Many of the existing methods for calculating displacement of slopes (e.g. Lin and Whitman, 1986; Ambraseys and Menu, 1988; Yegian et al., 1991b) use assumptions of original method of Newmark's rigid sliding block which does not involve dynamic response of deformable potential sliding mass during earthquake. In contrast to the original method of Newmark (1965) with the mentioned limitation, Makdisi and Seed (1978) presented a method of equivalent acceleration for seismic loading of the potential sliding mass based on the works of Seed and Martin (1966). When the horizontal equivalent acceleration of time history is applied to a potential rigid sliding mass, it causes dynamic shear stresses along the potential sliding surface, similar to the case of carrying out a dynamic analysis. Several common pseudo-static techniques are used to evaluate the stability of slopes, such as the methods introduced by Seed (1979), Hynes-Grifin & Franklin (1984), which all involve simplified assumptions. For instance, the two above mentioned methods have been calibrated for seismic assessment of embankment dams with maximum displacement of one meter for an appropriate seismic performance. In sum, these methods do not present an obvious and decisive criterion for seismic evaluation.

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The Seed (1979) pseudo static slope stability method has been developed for earth dams with crest acceleration less than 0.75g and with materials that do not tolerate serious decrease in resistance. In this method, using seismic coefficient of 0.15, the dam performance is described appropriate if the safety factor exceeds 1.15. In this method, characteristics of ground motion and dynamic response of sliding mass is expressed by a constant coefficient of 0.15 in all cases. Therefore in the mentioned method, the ground motion, dynamic resistance, and dynamic response of the embankment dam are considered very simple, as well as the fact that the level of conservatism is uncertain in the estimate and expected seismic performance.

In the method developed by Makdisi and Seed (1978), the first step is to evaluate the material's strength losing potential. They propose their method for cases where shear strength loss in materials is less than 10% to 20% of peak undrained shear strength. This method has been of highest usage in the recent decades, but as they have proposed, this method should be updated consistent with advances of new data. Since 1989 numerous records have been recorded whereas the method of Makdisi and Seed is based on limited number of records. Furthermore, ground motion caused by earthquake in a site is defined by peak ground acceleration (PGA) in the slope crest and magnitude of the earthquake. PGA is much variable in slope crest and therein frequency content of ground motion is not considered. Also

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the employed analysis method (i.e. method of slices and a limited number of 2D linear equivalent finite elements analysis), is relatively simple. Bray et al.'s (1998) Method is mostly based on the work of Bray and Rathje (1998) which in turn follows the works of Seed and Makdisi (1966), Makdisi and Seed (1978), and Bray et al. (1995). The methodology of this technique is based on the results of 1D decoupled complete nonlinear dynamic analysis (Matasovic and Vucetic, 1995), i.e. D-MOD, in combination with the Newmark rigid sliding block. In recent years, numerous dams have been designed in static and dynamic conditions based on the mentioned methods. Russel (1993), Wilson (2000), and Guoxi (2001) demonstrated that the behavior of embankment dams during earthquake can be better studied using dynamic analyses by numerical methods of finite elements and finite differences. Gurdil(1999) analyzed dynamic behavior of Kupru asphaltic core dam for levels of MCL and DBL using equivalent linear method. Ghanooni and Mahin Roosta (2002) analyzed an asphaltic core dam using linear equivalent techniques and nonlinear methods. They concluded that in nonlinear analysis, materials in transition zones at both sides of the core reach plastic state and experience large deformations whilst asphaltic core materials remain in elastic condition. Besides, Mahin Roosta (2007) studied seismic behavior of rockfill dams with asphaltic core against earthquake using linear equivalent techniques and nonlinear methods. Feizi et al. (2008) evaluated dynamic behavior of embankment asphaltic core dams using

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method of finite differences. Variety of the presented equations and methods related to behavior assessment of earth structure, including earth and Rockfill dams, in earthquake conditions shows that there is no secure and accurate method in this case, so requires more studies in this field. For instance, in the widely used pseudo-static method only one value is yielded as safety factor, which cannot provide an accurate evaluation of stability analysis of earth structures since the employed methods are based on simplified assumptions. Cases such as failure in Saint Fernando dam and Ushimatiling dam are evidence of weakness in pseudo-static methods as well. Accordingly, it may be incorrect and accompanied by much estimation to exert the effect of dynamic loading caused by earthquake by a constant without considering the complex nature of earthquake, PGA, and frequency content of different earthquakes. According to what was mentioned above, it seems that there is no method capable of offering a simpler and more realistic evaluation of stability related to dynamic behavior of embankment dams while being comprehensive and utilizing the most complete ones of the mentioned methods so this field needs further research.

Criteria for Seismic Stability Evaluation in Earth and Rockfill Dams

Seismic behavior of dams in passed earthquakes indicates that seismic events are not the principal cause of failure, since dams

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present a good behavior during earthquakes. However, there are not dams damage records of induced by intense earthquakes (Hernández et al, 2008). To control the stability of earth or rockfill dams during earthquake, different criteria can be taken into consideration. Different events may happen during earthquake which result in risks for dam performance. According to Ledbetter and Finn (1993), the effects of earthquake in failure of embankment dams are divided into four major categories, i.e. slopes instability, crest settlement, dam body cracking, and liquefaction. Regarding the existing observations and experiences, the probable causes of vulnerability in embankment dams against earthquake can be classified as following:

a) Fracture and dam collapse due to a main fault under dam body;

b) Failure occurrence in side slopes of dam due to earthquake motion;

c) Decrease in free board due to crest settlement or sliding of the slopes;

d) Sliding of dam body on weak layers due to earthquake loading;

e) Water overflow due to wave creation or land slide in the reservoir;

f) Break of spillway or water output pipes;

g) Liquefaction of saturated sands with low density or strength loss in saturated clays due to earthquake (in sensitive clays);

h) Formation of longitudinal cracks in vicinity of crest due to large tension strains caused by lateral vibration;

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i) Formation of lateral cracks due to tension strains caused by longitudinal vibration or different lateral response in neighborhood of lateral supports with steep slope or close to crest center.

According to the above mentioned issues, in order to consider an index or criterion for evaluation of seismic stability of dam, control of crest settlement or maximum shear strains can be chosen as parameters for investigation of appropriate seismic performance of earth and rockfill dams. In other words, in the case that the settlement of dam crest or maximum shear strains exceeds the allowable ranges, dam behavior during earthquake is assessed as unsuitable.

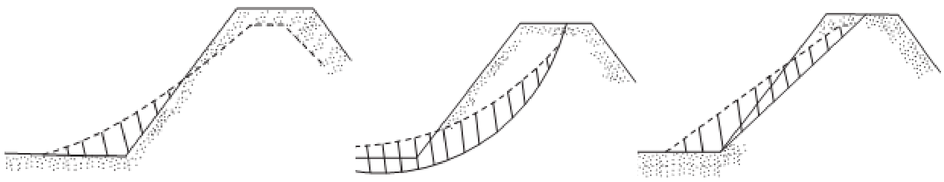

Fig. 1. Types of possible failure in embankment dams during earthquake [Das, 1993]

The Model under Study and its Characteristics

To explain the steps for calculation of safety coefficient in the suggested method, an asphaltic core dam is selected for case study and the procedure is presented using that.

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1. Geometrical Characteristics

The model considered in this research is a Rockfill dam with height of 75m and lateral slopes of 1:1.4 with an asphaltic core concrete of 1m width and filters of 4.5m width in both sides of the core.

For correct wave propagation in the model during dynamic analysis, dimensions of the model elements are considered to be small enough so that the following criterion suggested by Kuhlemeyer and Lysmer(1973) is satisfied:

$$\Delta l \leq \lambda/10$$

Where λ is the wave length of maximum input frequency of earthquake, and Δl is the size of the elements. Fig. 2 illustrates the geometry of designed model.

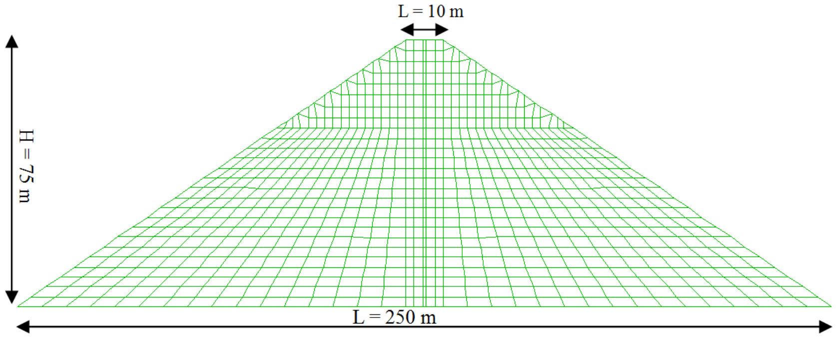


Fig. 2. Model of asphaltic core Rockfill dam, used in analyses

2. Material Parameters

To determine material parameters of dam body, we have used parameters belonging to a body of several Rockfill dams with asphalt core which have been executed in Iran. Table 1 exhibits these parameters.

Table1. Properties of the materials used in analyses

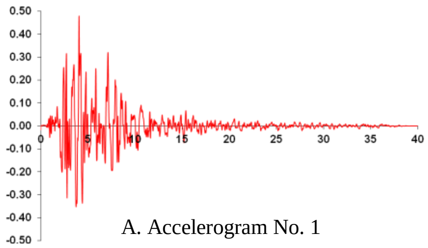
Materials	γ (kg/m^3)	C (kN/m^2)	φ (°)	E (kN/m^2)	ν
Asphaltic Core	2400	180	17	$1.5*10^5$	0.45
Filter	2100	0	32	$4*10^4$	0.3
Shell	2000	0	40	$8*10^4$	0.25

3. Accelerogram Selection

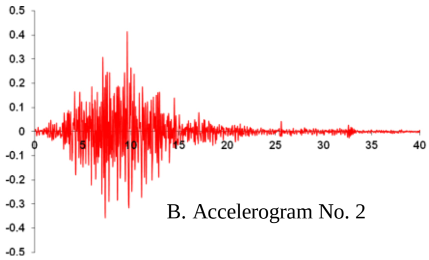
Several recorded data were studied in order to select the suitable input record of earthquake and three accelerograms with properties shown in Table 2 were used with the purpose of performing dynamic analyses. Fig. 3 illustrates the graph of these accelerograms.

Table2. Properties of three used earthquake records

No	Station	Geology	Earthquake Date	Magnitude	Epicentral Distance (km)	Component	PGA (g)
1	Coralitos-Eureka Canyon Road	Landslide Deposit	Loma Prieta, October 17, 1989	7.1(M_S)	7	90, 360	0.48
2	Santa Cruz-University of California at Santa Cruz	Limestone	Loma Prieta, October 17, 1989	7.1(M_S)	16	90, 360	0.41
3	Parkfield-Cholame Shandon No.2	Rock	Parkfield, June 27, 1966	5.6(M_L)	7	N65E, 21	0.48



A. Accelerogram No. 1



B. Accelerogram No. 2

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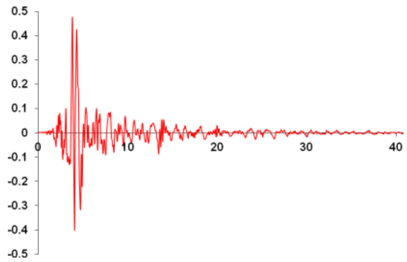

C. Accelerogram No. 3

Fig.3. Earthquake records used in dynamic analyses

4. Boundary Conditions

Regarding to lying of dam body on rock foundation, the underneath boundary is modeled as fixed. Furthermore, Rayleigh damping is employed in dynamic analyses for modeling damping of materials.

5. Methodology

Using a secure and accurate method is one of the existing challenges in seismic stability evaluation of geotechnical structures especially embankment and rockfill dams in earthquake conditions. Fadaee et al. (2009) compare different approaches for retrofitting of embankment dams such as adding berm and crest widening. To find the best retrofit scheme, they proposed some indexes such as crest settlement and maximum shear stress of dam body. Considering indexes proposed by them, the method presented in this research is carried out in the following steps: After creating a computer model of an asphaltic core rockfill dam with determined material parameters and geometrical conditions, static analysis is initially performed on the model. The analysis is carried out with the aim of controlling the model and truth of results together with using the stresses obtained from static analysis in dynamic analysis. In the next step, dynamic analysis is accomplished on dam model considering the record of a specific earthquake, which may be the record prepared from seismotectonic study of the site belonging to the dam under study. Then by increasing PGA of that record in appropriate ratios, a new record is created and is exerted to dam in dynamic numerical analysis. In each analysis, values of maximum crest settlement and maximum shear strain are recorded. As mentioned, the variables of crest's permanent settlement and maximum shear strain can be considered as criteria for controlling allowed deformations and seismic stability of an earth or rockfill dam. This procedure continues up to reaching crest's maximum allowable settlement or maximum allowable shear strain or occurrence of failure. In the method suggested in the current study, graphs of settlement and shear strain are illustrated versus PGA of the record based upon results obtained from dynamic analyses. Then, the PGA which causes a considerable increase in slope of this curve is recorded as dam's complete failure PGA. This PGA may be generated because of a considerable increase in either of the two graphs of settlement or maximum shear strain. By dividing this PGA by initial PGA of main record, a value is yielded which can be introduced as stability safety factor of dam in earthquake conditions under the used record.

6. Static and dynamic Analyses

Due to of the effects of static analysis results especially the resulting stresses on dynamic analysis; models are initially analyzed in

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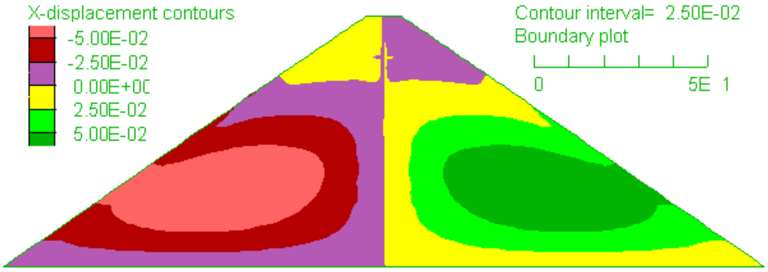
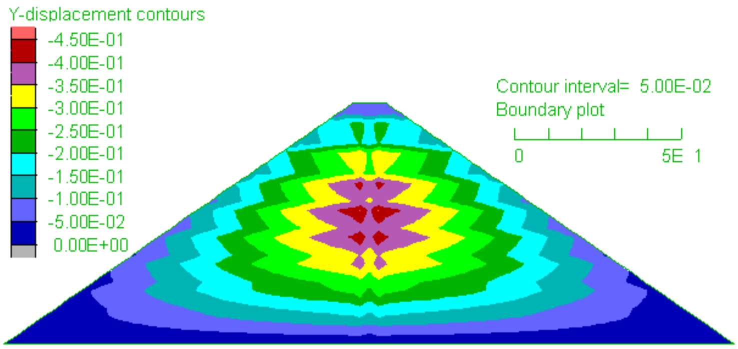
static conditions under stress-strain analysis prior to carrying out dynamic analyses. Hence, dam body construction is modeled layer by layer. Then after accuracy control of the results, in next step using the stresses obtained from previous steps, displacements caused by these analyses are changed to zero and analysis is performed on the models in earthquake conditions using accelerograms. Fig. 4 demonstrates horizontal and vertical displacements in static conditions at end of construction condition and Fig. 5 displays vertical stresses at end of construction.



Horizontal displacements



Vertical displacements

Fig.4. Horizontal and vertical displacements in static analysis at end of construction

Fig.5. Vertical stresses in static analysis at end of construction

Following static analysis on the used model, the displacements which are made in the model due to body construction are set to zero, while the created stresses remain for the next step. Subsequently, dynamic analysis is carried out on dam model using Loma Prieta earthquake (station: Coralitos) accelerogram as input record. Then according to the method of this study, a new record is prepared by an increase of 0.05 in the value of PGA of the used accelerogram without change in frequency content and analyses are repeated. The process of increasing the value of peak acceleration in each step by a constant amount of 0.05 relative to PGA of previous step is continued and the results obtained in each step are recorded. Continuing the mentioned procedure, when PGA value increases and reaches to 1.05, abrupt settlement and failure are observed in dam crest and analyses are stopped.

7. Interpretation of the Results

After employing the earthquake record, permanent displacements are made in dam crest. Fig. 6 shows permanent settlement of dam crest and in Fig. 7 acceleration response of dam crest is illustrated due

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to employing accelerogram of Loma Prieta earthquake (Coralitos station).

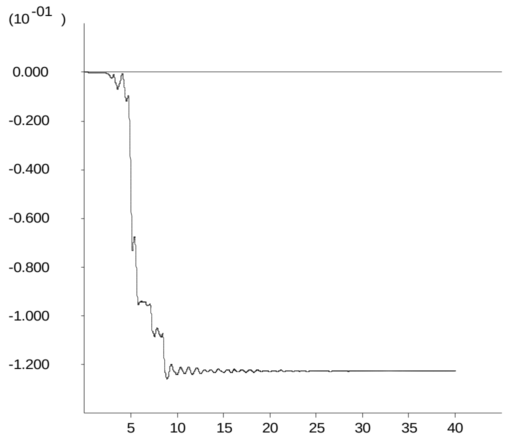

Fig.6. Vertical permanent displacement in crest after employing Loma Prieta earthquake record (Coralitos Station)

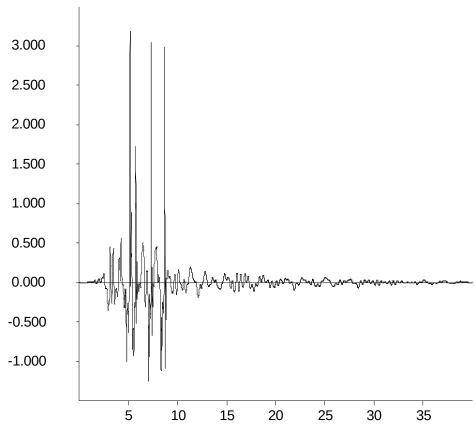

Fig.7. Acceleration response of dam crest after employing Loma Prieta earthquake record (Coralitos Station)

Analyses of the results indicate that shear strains along asphaltic core are less than other zones. This confirms that probability of crack occurrence in the core is negligible and, therefore, the asphaltic core effectively plays its water proofing role. In Fig. 8, graph of changes in

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shear strain along the asphaltic core is demonstrated after employing the record of Loma Prieta earthquake (station: Coralitos).

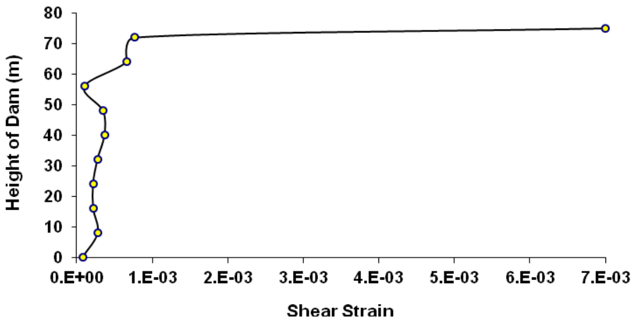

Fig.8. Graph of changes in shear strain along the asphaltic core after employing record of Loma Prieta earthquake (Coralitos Station)

In Fig.9, settlement contours in the dam crest area are shown after employing the Loma Prieta earthquake record (Station: Coralitos). According to this figure, vertical change in place at both sides of the core is more than core settlement.

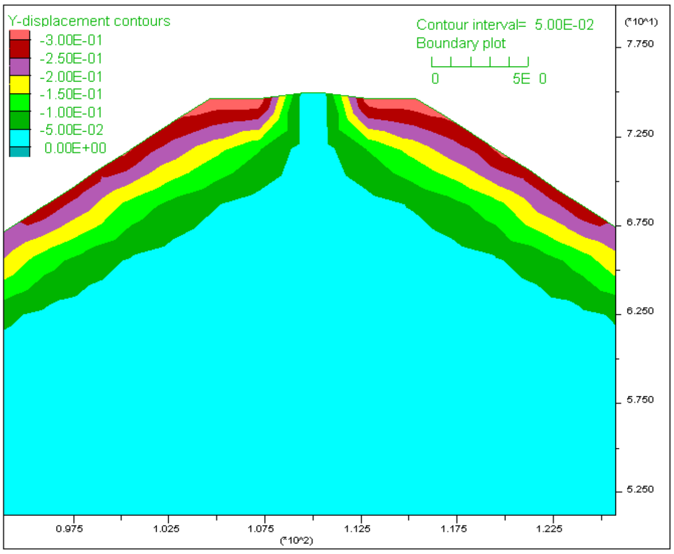

Fig.9. Settlement contours in dam crest area

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By applying an increase of 0.05 in PGA value of Loma Prieta record (Coralitos Station). At each analysis step, it is observed that permanent settlement of dam crest and also the maximum shear strain in dam body have a relatively constant increment. Following after PGA exceeds the value 1, crest settlement has an abrupt change. In this case, maximum shear strain shows a sudden increase at PGA values higher than 1, too. In Fig. 10, variation of crest permanent settlement is illustrated versus increase in PGA of the record, and Fig. 11 shows the graph of changes in maximum shear strain in dam body versus increase in PGA.

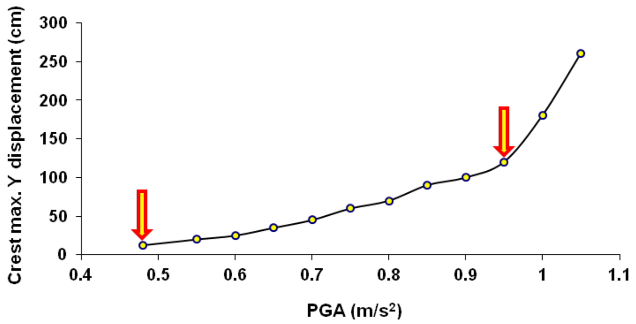

Fig.10. Variation of crest permanent settlement versus PGA increase

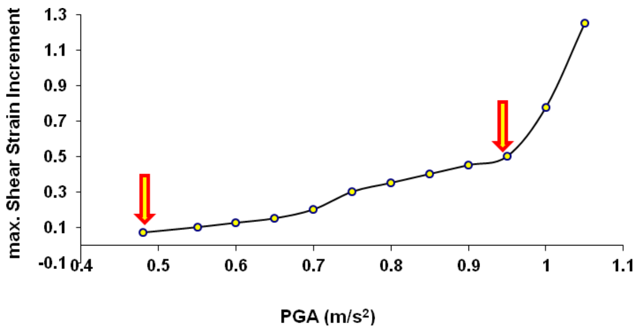

Fig.11. Variation of maximum shear strain in dam body versus PGA increase

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As the analyses of results indicate, increase in value of PGA of the record leads to increment of horizontal and vertical displacements of the crest. When maximum acceleration exceeds 0.95g, large increase is observed in displacements and dam crest fails finally. As a result, the mentioned PGA can be considered as maximum tolerable acceleration for this dam with specific geometrical characteristics and materials parameters. This acceleration is called “complete failure acceleration” in the present study. Dividing this value by initial PGA of the main record yields safety factor of 1.98 for seismic stability of this dam with mentioned characteristics.

$$Fs = \frac{(PGA)_f}{(PGA)_d} = \frac{0.95}{0.48} = 1.98$$

In the above equation, $(PGA)_f$ is complete failure acceleration and $(PGA)_d$ is maximum acceleration of the record. The suggested safety factor has been obtained for unfactored loads, and is of different nature compared to the safety factor obtained in pseudo-static analyses or Newmark’s sliding block analysis. This safety factor provides the possibility for engineer to judge about the distance between status of the existing condition and conditions which lead to complete failure during earthquake. Safety factors of seismic stability of dam based on proposed criterion using three acceleration records are presented in Table3. Also, variation of dam crest’s permanent settlement and maximum shear strain versus PGA increase for other two used records are shown in Figures 12 and 13.

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Table3. Safety factor of seismic stability of dam based on proposed criterion.

Record	Earthquake Date	$(PGA)_f$	$(PGA)_i$	Fs
Coralitos-Eureka Canyon Road	Loma Prieta, October 17, 1989	0.95g	0.48g	1.98
Santa Cruz-University of California at Santa Cruz	Loma Prieta, October 17, 1989	1.0g	0.41g	2.43
Parkfield-Cholame Shandon No.2	Park field, June 27, 1966	0.93g	0.48g	1.94
			Average	**2.12**

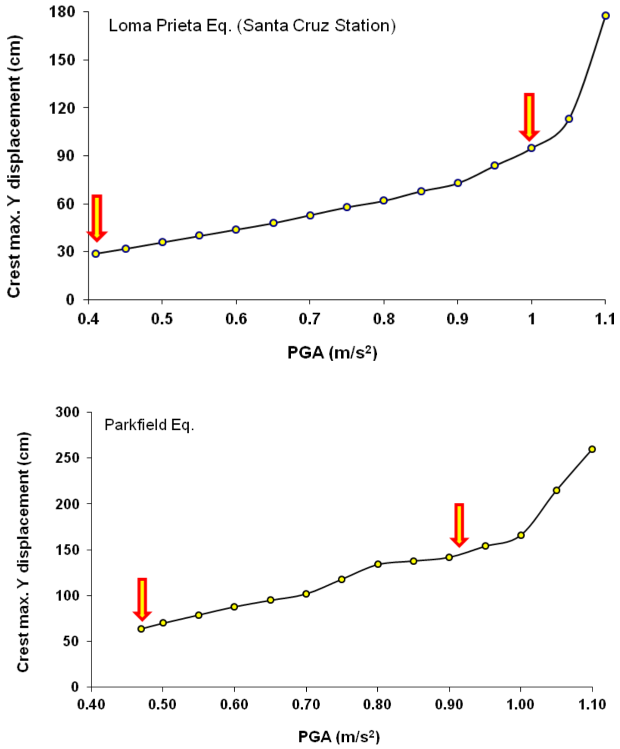

Fig.12. Variation of permanent settlement of crest versus PGA for other records

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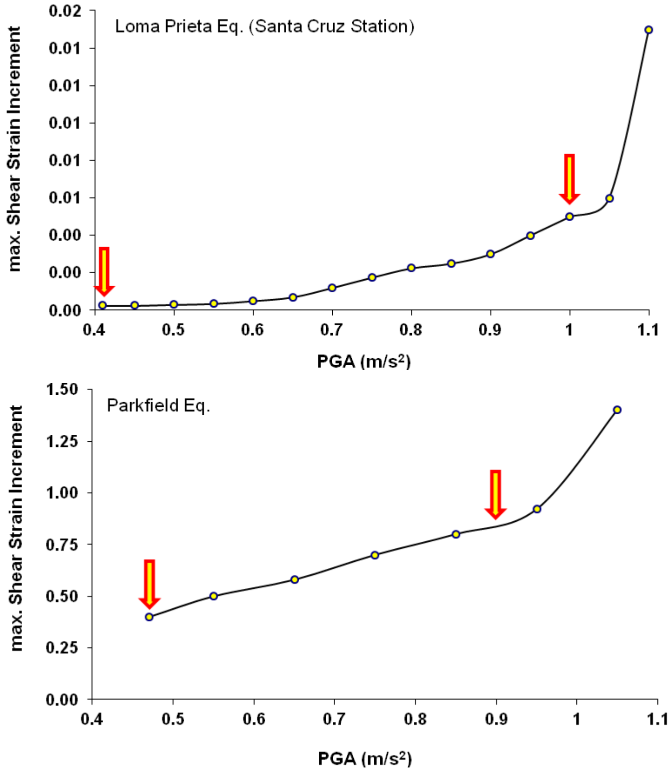

Fig.13. Variation of maximum shear strain versus PGA for other records

Conclusions

Numerous criteria have been proposed in recent decades to evaluate seismic stability of earth and rockfill dams. Nevertheless, the existing criteria for asphaltic core dams highly sensitive to settlements and strains do not effectively express the status of safety factor for seismic stability in some cases. In this research, a new evaluation criterion is proposed based on comparison of dam's failure acceleration and site acceleration. According to the suggested method,

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an increase in crest's permanent settlement and maximum strains is drawn versus increase in PGA in order to calculate safety factor for dam's seismic stability. Subsequently, the acceleration value which has caused a considerable change in slope of related curve is recorded as complete failure acceleration. Seismic safety factor is obtained from dividing this value by main PGA of the project's record.

In comparison with previous criteria, the proposed criterion has the advantage of not considering a pre-determined settlement value for failure. Rather, it estimates the settlement and strain at failure with regard to dam's geometrical and mechanical conditions. Furthermore, all effective factors such as record's frequency content, project's maximum acceleration, dam geometry, and dynamic properties of materials are considered in the suggested method for calculating seismic safety factor. In conclusion, the results of the proposed method in this research beside other existing methods can assist designers of asphaltic core dams in judgment about dam stability during earthquake occurrence.

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