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ABSTRACT

In current years the use of asphaltic concrete core dams are increased especially in some areas with shortage of clayey materials. These dams also have less earth work in comparison with clay core dams. Despite of many advantages of this kind of dam in compression of other types, the behavior of these dams against earthquakes and seismic condition isn't clearly specified.
In this research using CA2 program (Finite difference Code) Some numerical studies about the behavior of asphaltic concrete core dams with various height and slopes to understand the influence of dam geometry on behavior of these dams under earthquake condition were done.

Application of dams with asphalt concrete core is a relatively novel method especially in Iran. Iran is among regions with high seismicity risk. Therefore, investigation and studying the behavior of such types of dams in earthquake conditions is of more importance considering the novelty of implementing asphaltic core dams.
In this research, behavior of asphaltic core dams have been studied under earthquake loading using nonlinear dynamic analysis method and a method is presented for assessment of seismic stability of these types of dams in earthquake conditions based on nonlinear dynamic analysis.

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.

INTRODUCTION

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 to air conditions, simplicity of design and execution, not having the problem of land demesne for providing materials 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, there are some problems such as insufficient experience of contractors and also the required equipment, considering novelty of execution of such dams. Moreover, more study and investigation is essential about the behavior of these dams in different conditions especially during earthquake.

Since many dams are built or being built in seismic regions, their safe design against earthquake is of great importance. Careful study of seismic stability of earth and rockfill dams is one of the complicated problems in domain of geotechnical structures. The factors which play an important role in dynamic response of dam include: 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.

In this research, other than study of some existing methods and criteria related to seismic evaluation of dams, the behavior of an asphaltic core rockfill dam is evaluated.

SOME EXISTING METHODS

In a general classification, methods for dynamic analysis of earth dams can be divided into the three following 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.

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. 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 the 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 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 summation, these methods do not present an obvious and decisive criterion for seismic evaluation.

In method of Makdisi and Seed (1978), the first step is to evaluate the material’s strength loss potential. They propose the 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 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. (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 analyses (Matasovic and Vucetic, 1995), i.e. D-MOD, in combination with the Newmark rigid sliding block.

In recent years, numerous dams have been designed for static and dynamic conditions based on mentioned methods. Russel (1993), Wilson (2000), and Guoxi (2001) have demonstrated that 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 method of finite differences.

Variety and spread of the presented equations and methods related to behavior assessment of earth structure, including earth and Rockfill dams, in earthquake conditions is evidence that there is no secure and accurate method in this case, and 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.

CRITERIA FOR EVALUATION OF SEISMIC STABILITY IN EARTH AND ROCKFILL DAMS

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 results in risks for dam performance.

Regarding to 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 bord 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;

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 dam stability, 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.

MODEL AND ITS CHARACTERIXTICS

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.

Geometry

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) satisfies:

$\Delta l \leq \lambda/10$

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.

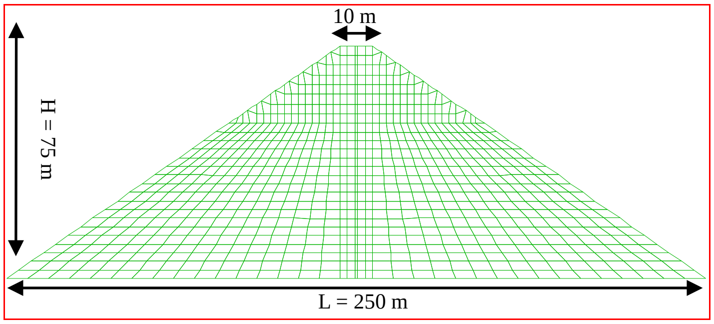


Fig. 2. Model of asphaltic core Rockfill dam, used in analyses

Material Properties

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

Table 1. 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

Accelerograph

Several recorded records were studied in order to select suitable input record of earthquake. One the other hand, according to locate dam body on bed rock, three accelerographs recorded on rock foundation with properties shown in Table 2 were used with the purpose of performing dynamic analyses. Fig. 3 illustrates the graph of the used accelerographs.

Table 2. Properties of three used earthquake records

No.	Station	Geology	Earthquake Date	Magnitude	PGA(g)
1	*Parkfield-Cholame Shandon No.2*	*Rock*	*Parkfield, June 27, 1966*	*5.6(M_L)*	*0.48*
2	*Coralitos-Eureka Canyon Road*	*Landslide Deposit*	*Loma Prieta, October 17, 1989*	*7.1(M_S)*	*0.48*
3	*San Francisco-Golden Gate Park*	*Siliceeous Sandstone*	*San Francisco, March 22, 1957*	*5.3(M_L)*	*0.11*

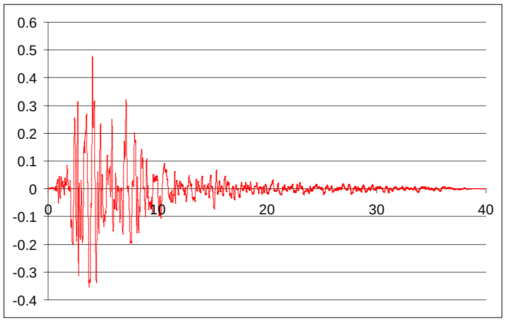


Fig. 3. Accelerograph of Loma Prieta earthquake used in dynamic analyses

Boundary Conditions

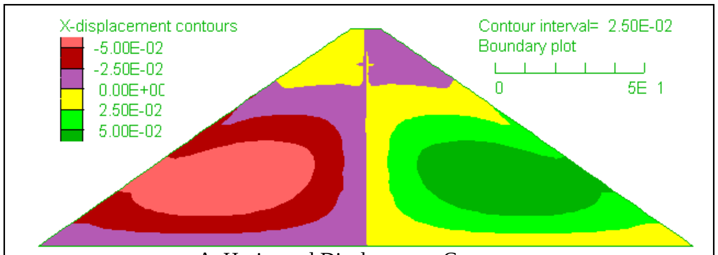
To take into consideration the boundary conditions regarding to lying of dam body on rock foundation, the underneath boundary is modeled as fixed. Furthermore, Reilegh damping is employed in dynamic analyses for modeling damping of materials.

USED METHODOLOGY

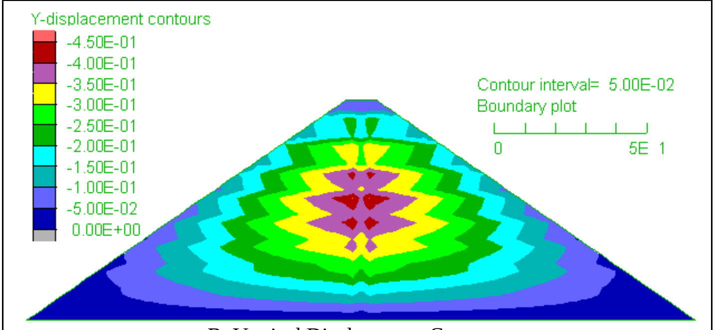
The method presented in this research is carried out in the following steps. After creating a computer model of an asphaltic core rockfill dam with determined material parameters and geometrical conditions, static analysis is initially performed on the model. The analysis is carried out with the aim of controlling the model and truth of results together with use of 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, the value of maximum crest settlement is recorded. As mentioned, the variables of crest’s permanent settlement 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 occurrence of failure. In the method suggested in the current study, graphs of settlement are illustrated versus PGA of the record based on results obtained from dynamic analyses. Then, the PGA which causes a considerable increase in slope of this curve is recorded as dam’s failure PGA. 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.

ANALYSIS

Because of the effects of static analysis results especially the resulting stresses on dynamic analysis; models are initially analyzed in 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 accelerographs. Fig. 4 demonstrates horizontal and vertical displacements in static conditions at end of construction condition.



A. Horizontal Displacement Contours



B. Vertical Displacement Contours

Fig. 4. Horizontal and vertical displacements 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 accelerograph 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 accelerograph 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.

INTERPRETATION

After employing the earthquake record, permanent displacements are made in dam crest. Fig. 5 shows permanent settlement of dam crest due to employing accelerograph of Loma Prieta earthquake.

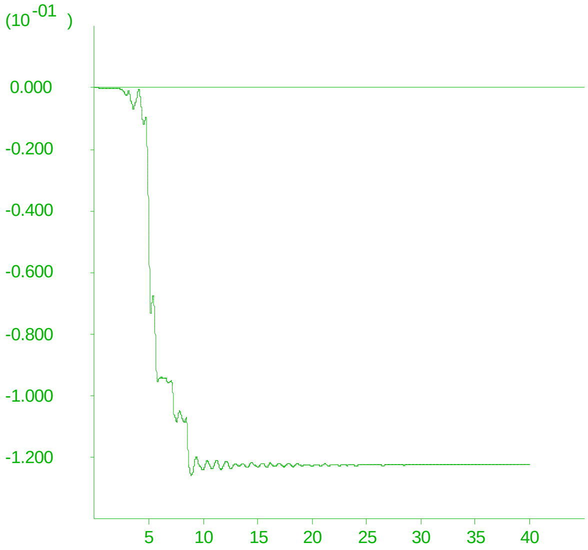


Fig. 5. Vertical permanent displacement in crest after employing accelerograph of Loma Prieta earthquake

In Fig. 6, settlement contours in dam crest area are shown after employing the earthquake record. According to this figure, vertical change in place at both sides of the core is more than core settlement.

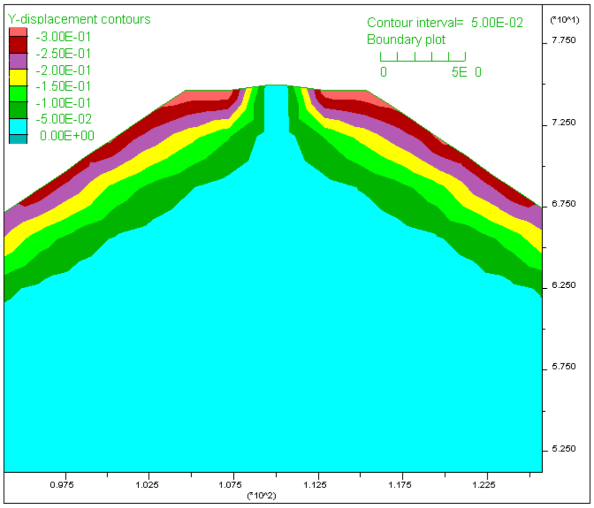


Fig. 6. Settlement contours in dam crest area

By applying an increase of 0.05 in PGA value of Loma Prieta record at each analysis step, it is observed that permanent settlement of dam crest has a relatively constant increment. Following after PGA exceeds the value 1, crest settlement has an abrupt change. In Fig. 7, graph of crest's permanent settlement is illustrated versus increase in PGA of the record.

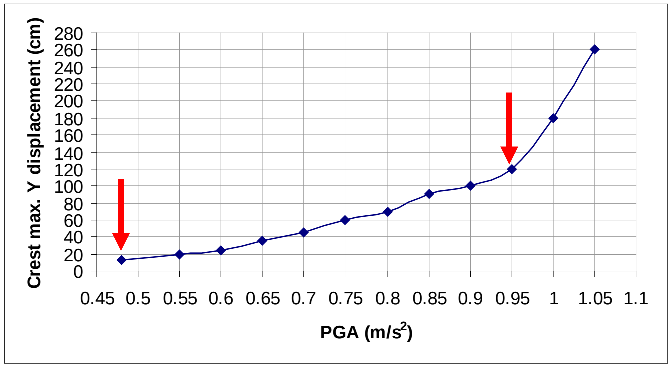


Fig. 7. Graph of dam crest's permanent settlement versus PGA increase

As the analyses 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. 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.

$$Fs = \frac{(PGA)_f}{(PGA)_d} = \frac{0.95}{0.4794} = 1.98 \qquad (1)$$

In above equation, $(PGA)_f$ is the acceleration at failure 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.

CONCLUSIONS

In this research, a new evaluation criterion is proposed based on comparison of dam's failure acceleration and site acceleration. According to suggested method, increase in crest's permanent settlement is drawn versus increase in PGA in order to calculate safety factor for dam's seismic stability. The acceleration value which has caused a considerable change in slope of related curve is divided by main PGA of the project's record to obtain safety factor in dynamic condition.

In comparison with previous criteria, the proposed criterion has the advantage that it does not consider a pre-determined settlement value for failure. Rather, it estimates the settlement 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, 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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