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Deformation Performance of the Karkheh Earth Dam with Mixed and Pure Clay Coreunder Seismic Excitations

S. M. Mir Mohammad Hosseini*[a], R. Bahrami[b], M. AsadolahiPajouh[c]

[a]*Prof, Civil Eng. Dept, Amirkabir University of Technology, Tehran, Iran*
[b]*M.Sc., Amirkabir University of Technology, Tehran, Iran*
[c]*M.Sc., Amirkabir University of Technology, Tehran, Iran*

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Abstract

The number of constructed dams has been largely increased due to high demands of water supplies, and earth dams are the most common types since they are more compatible to the environment. Nevertheless, the stability of these important structures during earthquakes has to be carefully evaluated and guaranteed. In the past, earth dams usually designed with pure clay core, but in recent decades they are widely designed and constructed with mixed clay core due to their better performance against vibrations particularly earthquake loadings.
This paper evaluates the displacement performance of the Karkheh Large Embankment Dam with mixed- clay core, recently constructed in south-western part of Iran, under earthquake motions and compares the dynamic analyses' results with those of pure-clay core. In this work, the Karkheh Dam with both mixed and pure clay core is numerically modeled using the FLAC 4.0software. After calibrating the model and completing the static and dynamic analyses under different excitations, belonged to some heavy past earthquakes, the results in terms of the maximum settlements, horizontal displacements of upstream and downstream shells are estimated, compared and discussed.
Based on the obtained results, it is noted that the dynamic performance of earth dams with mixed-clay core is more desirable than that of pure-clay core. It is also observed that the seismic settlements of the dam with pure-clay core averagely show an increase of 20 percents compared with that having the mixed-clay core.

Keywords:Karkheh earth dam, Mixed clay core, Dynamic analyses, Numerical modeling, Earthquake, Deformation

1.Introduction

Water supply has been the crucial problem of human beings in the world. Earth dams are often the most important structures to store and manage the main surface waters resources.
Due to wide utilization of earth dams in different areas particularly in zones prone to heavy earthquakes, it seems vital to assess the seismic safety of earth dams. Earthquakes may be endangering the dam stability, human life and devastating downstream cities. There are a significant number of seismic incidents during which these structures are subjected to partial or total damage. In recent decades, general studies have been conducted in this field and some approaches for the analysis of earth dams' dynamic behavior have been proposed. As a whole, the methods can be divided into two groups:
-Stability analysis Methods
-Response Analysis Methods
The pseudo-static and Seed and Martin (1966) methods are considered as stability analysis ones[1]. These Approaches are serving to calculate the safety factor against sliding. The methods known as shear beam, Jai Krishna (1962), Newmark (1965), Goodman and Seed (1966) [2-4], 1-D and 3-D Shear Wedge models are also the methods to determine the dynamic response of earth dams such as displacements, velocity, and period of different modes of vibrations. Dam response to an earthquake may be related to many factors such as dam geometry, mechanical properties of used soils, pre-seismic stress and pore water pressure distributions inside the embankment, and input motion characteristics. Most of these factors are partially or totally neglected by those approaches adopted to assess earth dam seismic safety [5]. The pseudo static approach, for instance, neglects some earthquake parameters such as frequency content and duration, known to significantly influence soil response. Compared to the pseudo static approach, the Newmark[3] method more realistically models the seismic loads using the actual acceleration time history of the earthquake.
The objective of this paper is to evaluate earth dams' performance under seismic loads and to investigate the effects of mechanical properties of core materials on the seismic responses of the dam. In this regard, first, Karkheh Large Embankment Dam, recently constructed in south-western part of Iran, is described in terms of its

Corresponding Author Email:mirh53@yahoo.com

Basic features namely geometry, and material properties. Then, a numerical model was developed for analyzing the dam by utilization of FLAC-2D[1] package. The developed model was calibrated by means of a series of precise instrumentation data. After investigating the validity of the adopted model, a comparative parametric study has been performed to bring out the effects of different core materials on the dynamic performances of the Karkheh dam.

2. The Karkheh Dam

The dam of Karkheh which is the largest reservoir earth dam constructed over the Karkheh River, in the south-west of Iran is thoroughly described in literature. Thus, in this paper only the features related to the dam geometry and material properties of the dam body are concentrated and explained. The height of the dam at its largest profile is estimated to 127 meters. Fig.(1-A) shows the maximum cross section of the Karkheh Dam. More than 1000 instruments have been mounted within the Karkheh dam along 23 sections all over its length. The instrumentations arrangement in the foundation and body of the dam at Section 5-5 (St. 1+230.00) which is highest one is shown in Fig. (1-B). At the first stage of design of the Karkheh Dam, its core material was decided to be pure clay; however, during the construction stage, it was decided to add some percents of coarse materials to the pure clay due to some advantages of such material for the dam core, compared to pure high plastic clay [7-8]. Regarding this fact, several experimental researches have been carried out on different types of gravel and clay mixture in order to get the optimum mixture percentage. The static experiments concerning permeability, direct shear, uniaxial and triaxial tests, consolidation, compaction and etc. The results of some of them are presented in figures 2 to 4.

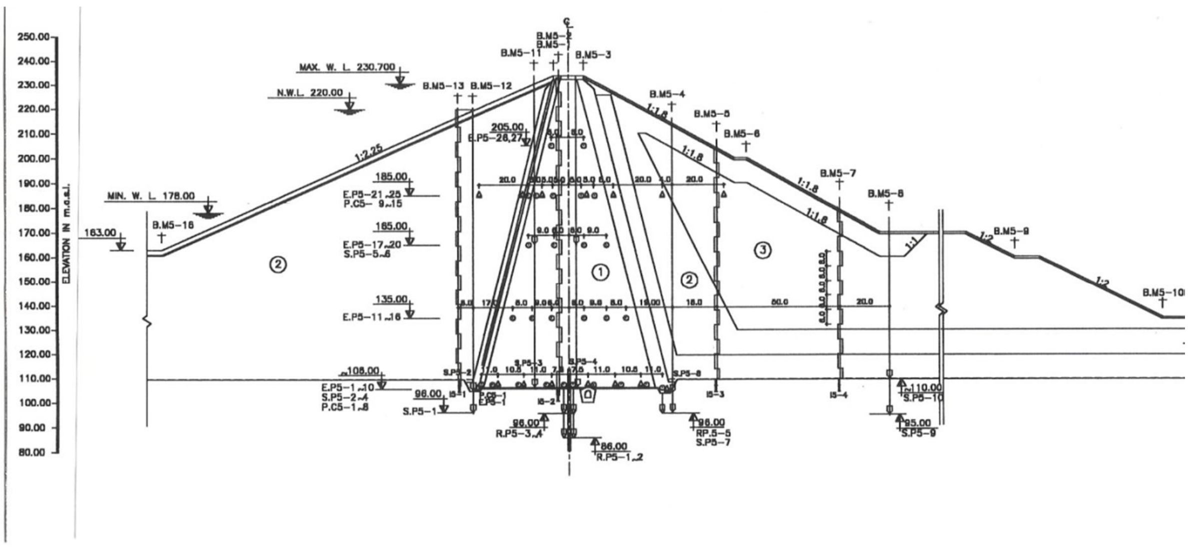

Fig.1. A.Maximum cross- section of the Karkheh Dam.

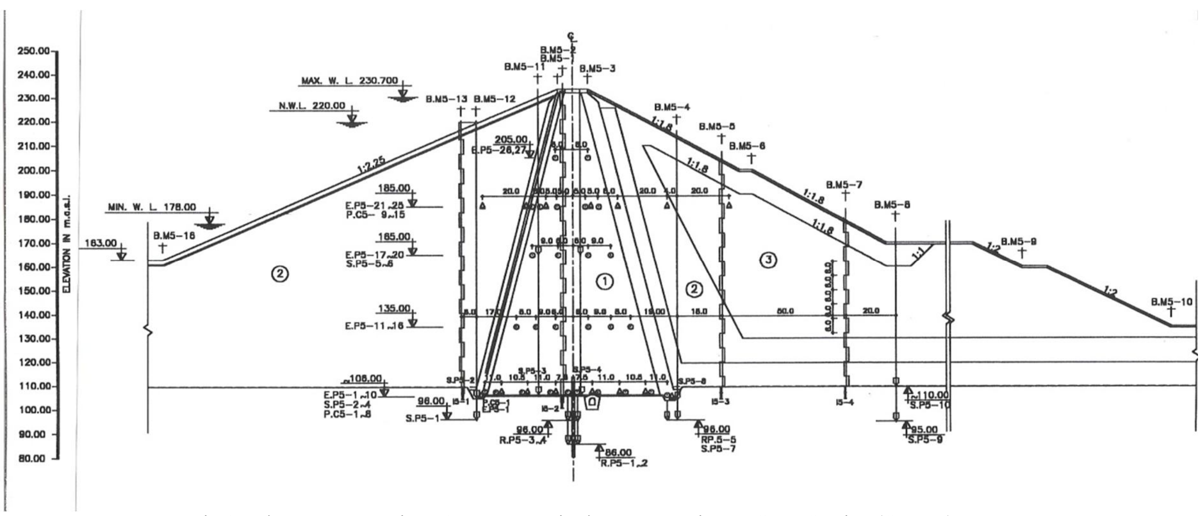

Fig.1.B.the Instrumentations Arrangement in the Dam Maximum Cross Section (Sec.5-5)

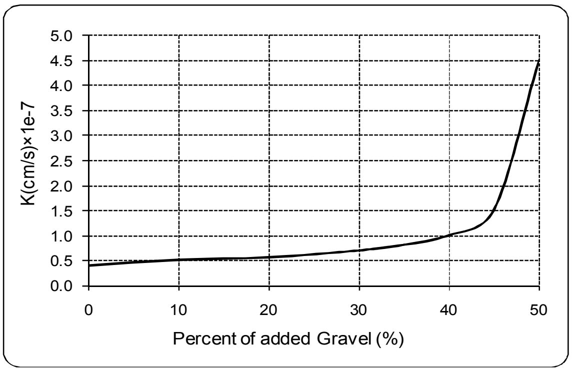

Fig.2.The variation of permeability coefficient by the percentage of gravel added to clay [7,8].

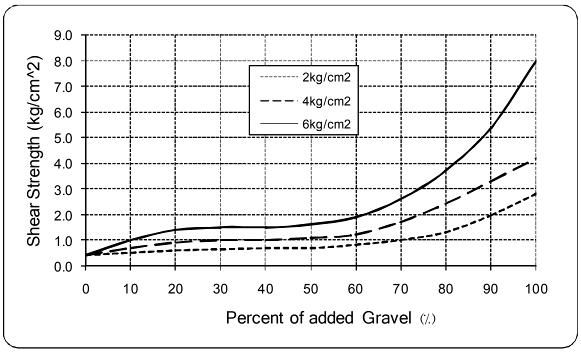

Fig.3.the variation of shear strength by the percentage of gravel added to clay [7,8].

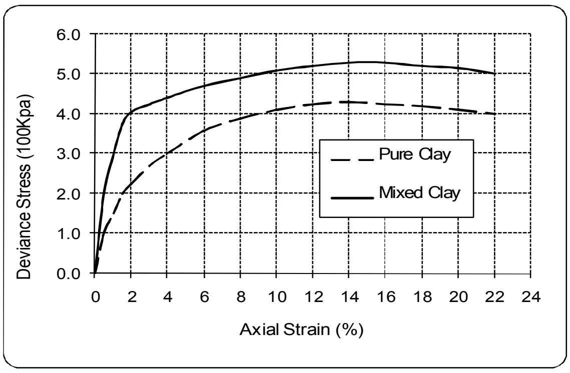

Fig.4. The stress-strain curve of mixed clay in comparison with pure clay at $\sigma_3 = 6\ (\frac{\text{kg}}{\text{cm}^2})$[7,8].

All of the static tests reveal the improvement of the properties of mixed clay compared with pure clay except permeability test. Based on the permeability tests' results, it can be observed that the variation of permeability in mixtures of low gravel percent (lower than 40%) is not considerable. However, the increase of coarse material percentage from the above limit enhances the coefficient of permeability considerably (Fig. 2). Finally according to these results, the best mixture for Karkheh earth dam core was achieved having the ratio of 40% gravel and 60% clay. More over the outcomes regarding to the shear strength illustrated in figures 3 and 4, show a significant grow in the shear strength and elastic module by an increase of the ratio of gravel to clay as expected.

Besides the static tests, some dynamic experiments have been carried out on the materials of the Karkheh earth dam core. Their results on the variation of the shear module and damping ratio with the shear strain level are presented in figures 5 and 6. Dynamic tests have been performed on the samples with the ratio of 40 to 60 for-

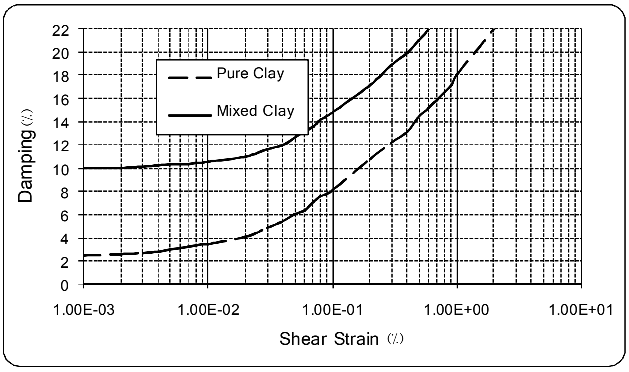

Fig.5.The variation of damping ratio of mixed clay in comparison with pure clay [7,8].

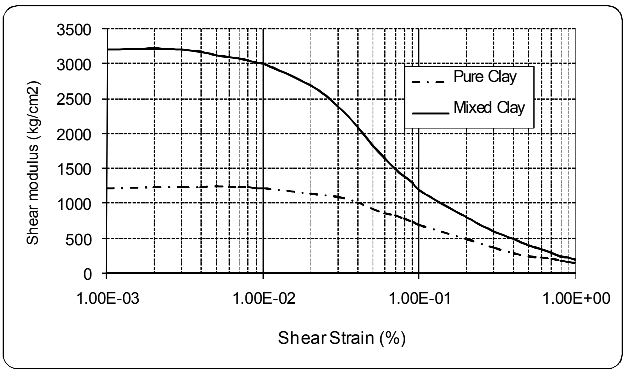

Fig.6.The variation of shear module versus shear strain level in pure and mixed clay at $\boldsymbol{\sigma_3 = 6\ (\frac{kg}{cm^2})}$ [7, 8]

Gravel to clay. It can be concluded that the shear module and damping ratio of the mixed clay have greater amplitude than the pure one.

3. The Numerical Model of the Karkheh Dam

Various constitutive models are available for the dynamic response of embankment dams to earthquake loading. These models range from the relatively simple hysteretic nonlinear models to complex elastic kinematic-hardening plasticity models.

Typical elasto-plastic programs used in practice to evaluate the seismic response of embankment dams are DYNA-FLOW [9], DIANA [10], DSAGE, DYNARD, and FLAC [6].

To simulate the Karkheh earth dam numerically, and to survey its dynamic behavior, the FLAC 2-D (Fast Lagrangian Analysis of Continua) software is used. The performance of this program is based on finite difference method which can be considered efficient approach for simulation of behavior of soil and rock or other materials especially with potential of plasticity. In the first step of the analysis process an appropriate mesh having different zones of dam body such as cofferdam, core, shell, filters and drain were developed as presented in Fig. 7.

The foundation of the dam is also modeled up to about 70 meters. The lateral boundaries were assumed to be lying at the distance of about 250 meters far from the heel and toe of the dam. In dynamic problems, boundary conditions should not cause the reflection of outward propagating waves back into the model. The elements are mainly tetrahedron with the dimension of 5×10 meters. Due to the sensitivity of results to the size of the mesh elements, it has been considered to utilize small elements; hence about 14 ones are used in modeling the core. Then, all the stages including primary conditions.
Preconstruction, construction phase and impounding were modeled step by step with the assumption of Mohr-

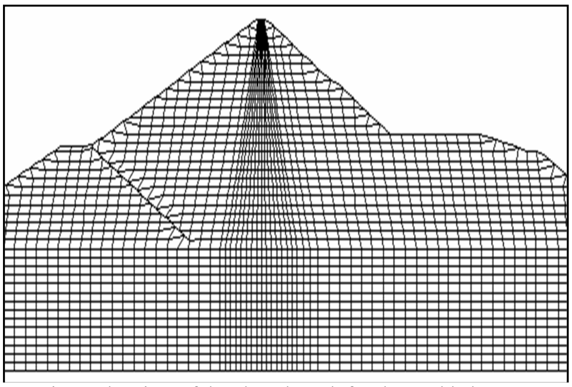

Fig.7. The view of developed mesh for the Karkheh Dam

Coulomb as the constitutive model for the materials and assignment of the proper parameters.
In modeling the primary conditions of preconstruction, all layers of the dam's body were made inactive (Null), suitable parameters were allocated to the foundation materials, then the existing primary stresses in three main directions and also pore pressure, presuming free water level at the river bed, are applied to the model. Finally by the imposing the gravity acceleration to the model and analyzing it and also making the displacements zero, the conditions were prepared for modeling the dam. Afterwards modeling was developed according to the construction process in some phases. In this study the whole dam's body height is divided into 26 layers, of 5 meters thickness. This was achieved after some trial efforts in order to reach an optimum mesh system for the dam under study.
The simulation stage followed these steps: first all layers of cofferdam were activated one by one and the required analyses were done at each step. The two calculations carried out on each layer were mechanical and seepage analyses. In the mechanical computing, due to pore pressure development in the core, the materials were not supposed to be drained. Secondly, similar to the real condition, the materials were allowed to consolidate and the pore pressure to dissipate consequently during the time of each layer's construction. By the start of the reservoir impounding, the modeling of the dam body and impounding were carried out simultaneously.

4. The results

4.1. The Static Analysis Results

The variables such as the settlements and pore pressures were evaluated for the purpose of model calibration. Figures 8 and 9 present the pattern of vertical and horizontal displacements induced in numerical analyses up to 3/29/2005 (corresponding to 9/1/1384 ,after completion of the construction and also impoundment of the dam) respectively and the developed pore pressure is shown in Fig. 10 as well.
The maximum values of these variables are located at the 1/3 of the dam height from the foundation. The topmost amount of the settlement after the model calibration equals to 160 centimeters corresponding with the value measured by the dam instruments. Furthermore, the maximum pore pressure in numerical model was estimated 1050 KPa which was very close to 1000 KPa, measured by mounted piezometers, in the dam body[11]. Based on the results a good agreement exists between the instrumented values and the numerical results, verifying the precision of the model and selected parameters. Meanwhile the maximum values of horizontal displacements of upstream and downstream shells were measured as 40 and 50 centimeters respectively.

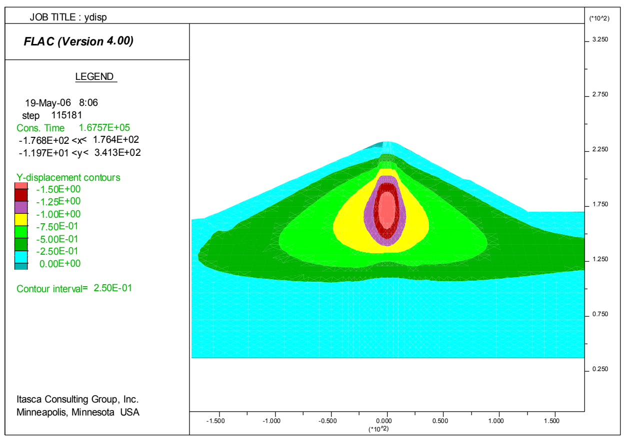

Fig.8. The pattern of static settlements in numerical models

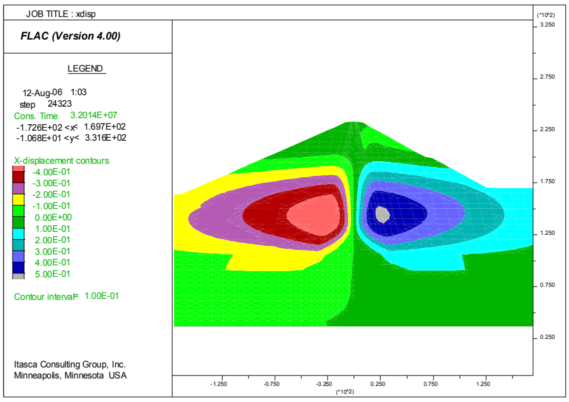

Fig.9. The pattern of static horizontal displacements in numerical models

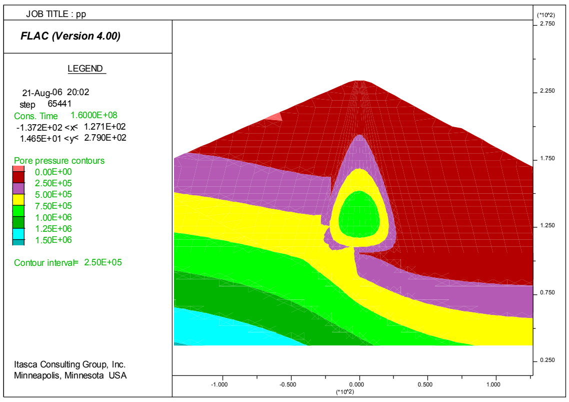

Fig.10.the pattern of pore pressure development in numerical models of static analyses

Since one of the most significant goals of this work is to compare the displacements of earth dams with mixed and pure clay core, another model with similar process was analyzed except the properties of the core which considered as pure clay material. As explained before, all phases, namely; before construction, stage construction and the impounding of the dam were also conducted. Although the patterns of induced variables in both models are similar, their values differ substantially. At the end of static analyses, the maximum settlement of the core for dam with mixed clay core was about 40% and the horizontal displacements of upstream and downstream shell were about 20% lower than those estimated for the dam with pure clay core. The strength parameters of pure and mixed clay after calibration and the parameters assigned to the materials of other dam zones are offered in tables (1) and (2) respectively.

Table 1. The strength parameters of mixed and pure clay

The parameter	E(MPa)	Φ(Deg.)	C(kg/cm^2)	Ψ(Deg.)
mixed clay	35	20	0.3	2
pure clay	20	14	0.35	2

Table 2. The strength parameters of Karkheh Dam's materials

The parameter	Shell	Filter & Drain	Mudstone Layer	Conglomerate Layer
E(MPa)	85	70	120	900
Φ(Deg.)	39	35	22	39.4
C(kg/cm^2)	-	-	0.7	0.85
Ψ(Deg.)	10	8	5	12

4.2. The Dynamic Analyses Results

By the completion of the static analyses and calibration, the prepared models were considered as the primary conditions for dynamic analysis. Imposing the suitable boundary conditions, assignment of dynamic factors such as shear module and damping ratio and also the way of applying the dynamic loads are known as the most factors influencing the dynamic analyses.

The boundary conditions in FLAC software for dynamic problems should be defined not to cause the reflection of outward propagating waves back into the model and lead to complete absorption of received waves to the boundaries. Hence in this study the boundary conditions also account for the free-field [6].
Moreover, due to shortcomings of the experimental data, empirical curves have been used for estimation of dynamic parameters of the materials of dam body and foundation [12].
One of the proposed formulas for estimation of G_{max} for granular materials known as Seed &Idriss, (1986) equation is Eq. (1) [13].

$$G_{\max} = 21.7\, P_a\, k_{2\max} \left(\frac{\sigma_0'}{P_a} \right)^{1/2} \quad (KPa) \qquad (1)$$

The only unknown parameter in the above equation is k_{2max} which can be defined by using proposed empirical curves. One of these diagrams is shown in Fig. (11) as an example. The value of k_{2max} is taken 140 for shells and 50 for filter and 40 for mixed core, according to the experimental results carried out on Karkheh earth dam materials [8]. Since the major part of the material consist of grains, Seed &Idriss (1986),[13], relation seems suitable. Meanwhile the value of G_{max} for foundation material has been derived from the results of measured shear wave velocity and regarding equation (2) [13].

$$G_{\max} = \frac{\gamma}{g} v_S^{\,2} \qquad (2)$$

It should be noted that shear wave velocity in foundation material is also derived from the in situ tests as 1000 $^{m}/_{s}$ [14]. The ultimate values of k_{2max} and G_{max} used in the analyses of Karkheh dam with mixed clay core are given in Table (3).
In respect to the numerical analysis of dam with pure clay core, the maximum shear module is taken similar to the casewith mixed clay except thatfor the core. To obtain G_{max} of pure clay core the relation suggested by Seed &Idrss (1986), for clay deposits is used [13].

$$G_{\max} = \frac{625}{0.3 + 0.7e^2} P_a \left(\frac{\sigma_0'}{P_a} \right)^{1/2} \qquad (3)$$

Further, Rayleigh damping of 5% has been assumed for all zones of dam for the purpose of depreciation energy.
After assignment of dynamic parameters and definition of boundary conditions, it is time to apply the dynamic loads to the models. In FLAC, the dynamic input can be applied in one of the following ways:

(a) An acceleration history;
(b) A velocity history;
(c) A stress (or pressure) history; or
(d) A force history.

Table 3. The amounts of $k_{2max}$and G_{max} for various materials of Karkheh dam with mixed clay core.

Materials	$(k_2)_{max}$	G_{max}(KPa)
Foundation	-	$2e6$
Filter	50	$G_{max} = 21.7P_a(50)(\frac{\acute{\sigma}_0}{P_a})^{1/2}$
Mixed Core	40	$G_{max} = 21.7P_a(40)(\frac{\acute{\sigma}_0}{P_a})^{1/2}$
Shell	140	$G_{max} = 21.7P_a(140)(\frac{\acute{\sigma}_0}{P_a})^{1/2}$

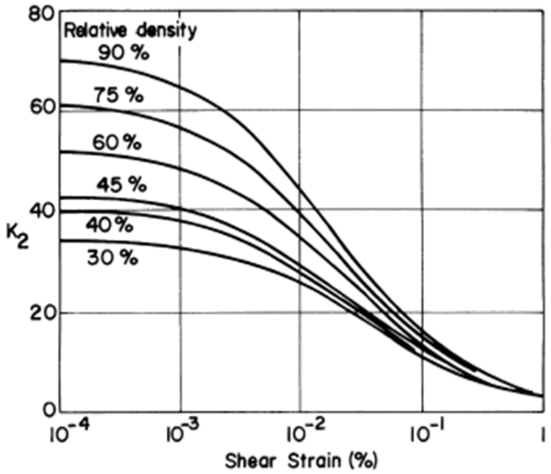

Fig.11. The different values of k_2 for different relative density in sand soils [13]

Dynamic input is usually applied to the model boundaries. Accelerations, velocities and forces can also be applied to interior grid points. The selected accelerations were refined based on the dimension of the elements and in order to providing the numerical accuracy of wave transmission were filtered up to 5 Hz. Further, based on the past seismic studies carried out in the region the PGA of 0.4 g. was used to calibrate the selected acceleration time histories. In this work the accelerations of earthquakes: Tabas, Taft and El Centro are used and presented in following figures.

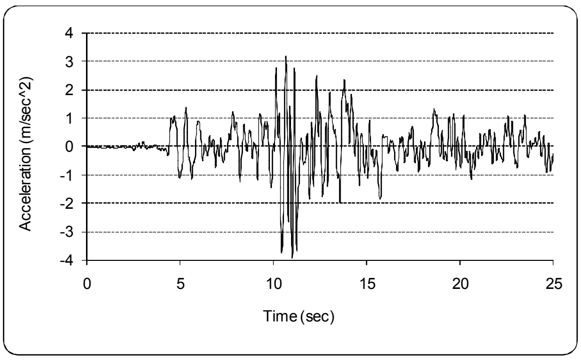

Fig.12. The acceleration time history of Tabas earthquake filtered for the frequency 5Hz and calibrated for 0.4g

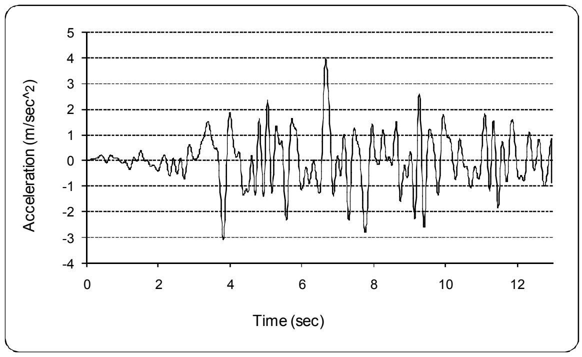

Fig.13. The acceleration time history of Taft earthquake filtered for the frequency 5Hz and calibrated for 0.4g

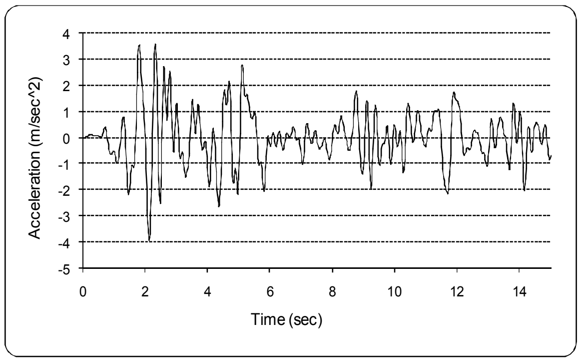

Fig.14. The acceleration time history of El Centro Earthquake filtered for the frequency 5Hz and calibrated for 0.4g

Applying above accelerations to the base of the models, substantial displacements appeared in numerical models. The patterns of created deformations in both models with pure and mixed clay under various seismic excitations were the same however; they differ with each other quantitatively. Figures 15 and 16 illustrate the patterns of dynamic vertical and horizontal displacements respectively.

It can be inferred that the maximum settlement occurred at the high levels of the core and its center; as well the maximum horizontal displacement occurred on the upstream and downstream slopes. Tables 4 to 6 present the values of induced displacements in the models under different earthquake accelerations.

Based on the results, smaller displacements are observed in the model of mixed clay core, which prove desirable seismic performance of earth dam with mixed clay core compared with that of pure clay one. In figures (17) and (18) the settlement history of crown excited by the acceleration of earthquake Tabas is presented.

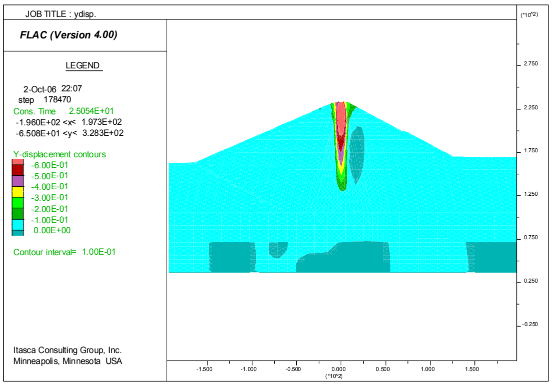

Fig.15. The pattern of dynamic settlements in numerical models of the Karkheh Earth Dam

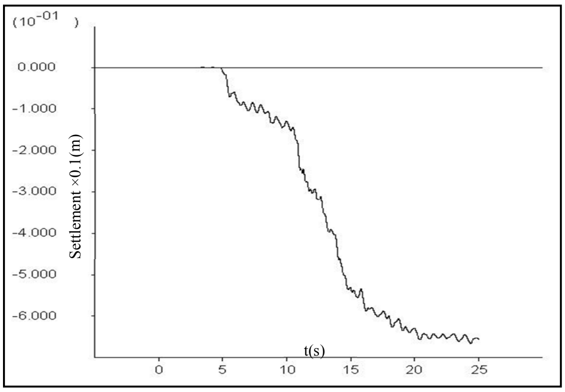

Fig.17.The history of dynamic settlements of the center of core at the level of the crown in the model with mixed clay core

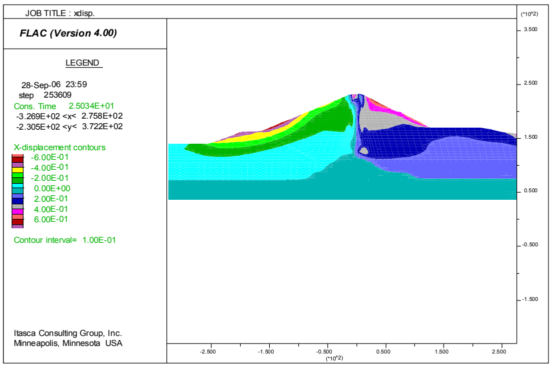

Fig.16.The pattern of dynamic horizontal displacements In numerical models of the Karkheh Earth Dam

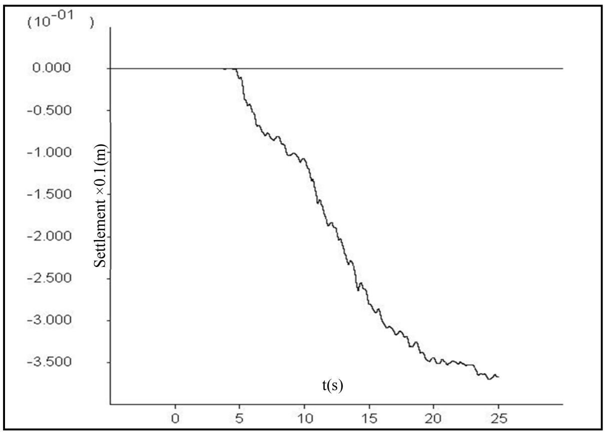

Fig.18.The history of dynamic settlements of the center of core at the level of the crown in the model with pure-clay core

Table 4. The maximum settlements under seismic excitations.

The Acceleration	Model with mixed clay core (cm)	Model with pure clay core (cm)
Tabas	65	90
Taft	55	65
El Centro	84	100

Table 5- The maximum horizontal displacements of upstream shell under seismic excitations.

The Acceleration	Model with mixed clay core (cm)	Model with pure clay core(cm)
Tabas	-60	-65
Taft	-40	-40
El Centro	-70	-75

Table 6. The maximum horizontal displacements of downstream shell under seismic excitations

The Acceleration	Model with mixed clay core (cm)	Model with pure clay core(cm)
Tabas	70	80
Taft	75	80
El Centro	85	90

5. Conclusions

Since the pore pressure developments of the Karkheh Dam under seismic loads have been studied previously [15], in the present work, the displacement responses of the Karkheh Dam with mixed and pure clay core under seismic loads are investigated and compared. In this regard, firstly we modeled the Karkheh Dam with both mixed and pure clay core by the FLAC 4.0 software [6]. After assigning of suitable primary material properties to the model with mixed clay core, it was analyzed statically .The model was then calibrated using the instrumentation data collected from the Karkheh site. The model was further reanalyzed for the dam with pure clay core.
As a whole the analyses done in static and dynamic domains clarify the high performance of earth dam with mixed clay and low-level displacements. The most important results of static analyses can be summarized as following:

1) The vertical and horizontal displacements will increase by an increment of embankment level.

2) In all stages, settlements and pore pressure of greater values occurred in the model of pure core compared with those of mixed core. At the end of static analysis the maximum settlement of the pure core was evaluated 40% greater than the other model. In addition the maximum water pore pressure in the dam with pure core was measured 25% more than that of the h mixed core.

3) The horizontal displacements of the dam with pure-clay core averagely show an increase of 20 percent compared with that having the mixed-clay core.
4) In both models, by increasing the embankment level, the induced water pore pressure during the construction is increased.
5) It was observed that in both models maximum pore pressure was created in the core center and at the level of about 1/3 of the dam height. It is reduced when moving toward the filter.

Among significant results of dynamic analyses the maim findings can be mentioned as bellow:

1) The maximum settlement of the dam in both models happened at the upper levels of the core and its center as well.

2) The maximum horizontal displacement occurred on the upstream and downstream slopes; the horizontal displacement of upstream shell was towards the upstream and similarly the horizontal displacement of downstream shell inclined toward the downstream.

3) It can be concluded that the settlements of the dam with pure clay core are assumed averagely 20% greater than those of the dam with mixed core.

This dynamic research can be accounted as a starting point and it is expected to be improved and refined by using more accurate data in future.
Based on the obtained results, it is noted that the dynamic performance of earth dams with mixed-clay core is more desirable than that of pure-clay core. It is also observed that the seismic settlements of the dam with pure-clay core averagely show an increase of 20 percent compared with that having the mixed-clay core.

References:

[1] Seed, H.B. and Martin, G.R., (1966), “Theseismic coefficient in earth dam design “, J. Soil Mech. & Found. Eng. Div. 92(SM3), 25-58.

[2] Jai Krishna (1962),” Earthquake resistant design of dams”, Earthquakes Journal of the Engineering Mechanics Division,. ASCE, Vol. 85(EM4), 109-129.

[3] Newmark, N.M. (1965), “Effects of earthquakes on dams and embankments”, Geotechnique, 15, 139-160.

[4] Goodman, R.F. and Seed H.B. (1966), “Earthquake induced displacements in sand embankments”, J. Soil Mech. And Found. Eng. Div., 92(2), 125-146.

[5] Ozkan, M.Y. (1998), “A Review of Considerations on Seismic Safety of Embankments and Earth and Rock-Fill Dams”, Soil Dynamic and Earthquake Engineering, Vol. 17, 439-458.

[6] Itasca Consulting Group, FLAC: Fast Lagrangian Analysis of Continua, vol. I. User's Manual, vol. II. Verification Problems and Example Applications, Second Edition (FLAC3D Version 3.0), Minneapolis, Minnesota 55401 USA, 2005.

[7] Mir Mohammad Hosseini, S.M. (2002), “Performance of Mixed-Clay as Core Material for Earth Dams”, Electronic Journal of Geotechnical Engineering, Vol. 7.

[8] Mir Mohammad Hosseini, S.M., et al., (2003), “Dynamic and Static Properties of Mixed- Clay as Core Material of the Karkheh Large Embankment Dam”, Proc. 21th ICOLD Congress, Question 83, R. 20, Montreal

[9] DYNAFLOW Manual, A Nonlinear Transient Finite Element Analysis Program, Department of civil & environmental engineering. Princeton University, New Jersey, 08544-5263.

[10] DIANA Maual, Analysis b.v.P.O.1132600 AC Delft the, Netherlands, Web site address: http://www.diana.nl/.

[11] Iran Water and Power Resources Development Co., (2005), “The Summery of Evaluation of Precise Tools’ Results in the Body and Foundation of Karkheh Large Embankment Dam’s Studies”.

[12] Seed, H.B. (1980), “Earthquake- Resistance Design of Earth Dams”, Symposium on Problems and Practice of Dam engineering, Bangkok, 41-59.

[13] Seed, H.B., Wong, R.T., Idriss, I.M., Tokimetsu, K. (1986), “Moduli and Damping Factors for Dynamic Analysis of Cohesion less Soils”, Journal of Geotechnical Engineering, Vol. 112, No. 11, 1016-1022.

[14] Iran Water and Power Resources Development Co., (2001), "The Summery of First Stage of Karkheh Large Embankment Dam's Studies".

[15] Nasrollahi, S.M., (2004), "The Evaluation of the Pore Pressure in Mixed-Clay as Core Material for Earth Dams while Earthquake Compared with the Ones of Pure-Clay, the Karkheh Large Embankment Dam as a case study", M.Sc. Thesis, Amirkabir University of Technology, Tehran-IRAN.