A comparison between seismic behaviors of earth dams with inclined and vertical clay cores- a numerical analysis approach

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ABSTRACT:

A 67m high existing embankment dam with an inclined clay core (Bidvaz Dam) in Iran is analyzed numerically for the earthquake loading (the Tabas Earthquake). The analysis is repeated for the same dam, but with the assumption that the core is vertical. The analyses are carried out with FLAC computer code, which is based on the finite difference technique, and employing the Mohr Coulomb elasto plastic constitutive model to define the mechanical behaviors of the dam materials. The dams' construction loading are simulated using effective strength parameters of the dam body materials with computing pore pressure developments in the core during construction. The analysis for the earthquake loading is performed using the total strength parameters of the materials. The results of the analyses for both of the dams are carefully evaluated and compared. The main results are summarized as follows: For the pre-earthquake (end of construction) loading, the deformations developed in the dam body are comparatively larger for the dam with the inclined core, while the excess pore water pressures in the core are comparatively higher for the dam with the central core. For the earthquake loading, the deformations developed in the dam body are comparatively larger for the dam with the inclined core. Sensitivity analyses with various peak ground accelerations indicate that the dam with the inclined core is more susceptible to earthquake-induced instability.

KEYWORDS: Numerical analysis, Earthquake loading, Earth dam, Inclined core.

1. INTRODUCTION

A considerable number of dams, mainly earth dams, are currently under design, construction, or operation in Iran. All of the recent large dams in the country, including earth dams, are equipped by a variety of instruments and being monitored in regular bases [1].
This paper presents numerical analyses of an earth dam, with inclined clay core, located in the North-East part of Iran. Profiles of settlements, stresses and pore water pressures during the dam construction are presented. Some of the analyses results are compared with the instrumentation monitoring results. The dynamic analysis with response spectra method is used for the prediction and comparison of deflections before and after earthquake.
The dam once is assumed to have a vertical clay core, with the same volume of core material. Results of dynamic analyses of the two dams (the real dam with inclined core and the hypothetical dam with vertical core) are compared and presented in this paper.

2. DAM CHARACTERISTICS

1.1. Geometry

The Bidvaz earth dam with an inclined clay core and a maximum height of 67 m was constructed on the Bidvaz River, Khorasan, Iran. The main purpose of the dam construction is to provide water for irrigation. The longitudinal section and the highest cross section of the dam are shown in Figures 1 and 2, respectively. The coffer dam is integrated in the main dam. The crest length is 104 m, the crest width is 11 m, and the capacity of the dam reservoir is about 53 million m^3 [3].

1.2. Materials

The core materials consist of clay soils, classified as CL, with 90% fines and 10% sand and gravel, compacted in layers of 20 cm final thickness in 96.5% of standard proctor compaction. The optimum moisture contents 19% and the average compaction moisture content is ω_{opt}+2%. Other soil parameters are: LL=33.6%, PL=16.5% and natural moisture content =17.6%. The downstream and upstream shell materials are ballast and rockfill classified as GP-GC and GC-GM with Dr=84% and natural moisture content=12%.
The foundation consists of a coarse, very dense alluvium layer with a thickness of about 23 m below the dam core area and a limestone layer below the dam shells.

3. INSTRUMENTATION AND MONITORING

Three cross sections of the dam, Sections C-C, F-F, and H-H, as shown in Figure 1, are instrumented with pressure cells, piezometers, standpipes, settlement gauges, and inclinometers. Some of the instruments, mainly piezometers, were either subjected to damage during construction or did not work properly. We excluded these instruments from our study. The instrumentation design of section F-F, which is typical of the other sections, is presented in Figure 2 [1, 3].

4. NUMERICAL ANALYSIS

4.1. During Construction

The numerical analyses were carried out using FLAC2D [2] computer code on a plane strain idealization of the highest cross section of the dam (Section F-F). Effective stress mechanical parameters were introduced into the analyses, which include the computation of the pore water pressure development in the core during construction. An elastic model is used for the rock foundation material and the Mohr-Coulomb elasto-plastic behavior with a non-associated flow rule is employed for the dam body materials. Table 1 presents the material parameters used in the numerical analyses. The dam body was divided into 26 construction layers, each layer 2.5 m high, to simulate the construction stages. The finite difference mesh for the dam is shown in Figure 4.To eliminate the effect of boundaries on the analyses results, 100 m of the foundation in both sides of the dam body was included in the mesh. The depth of the foundation included in the modeling was 33 meters. The construction loading was simulated by the stages involved in the dam construction. For the modeling of the in-situ stresses within the dam foundation, at first, all layers of the dam body were nulled and then, the switching on gravity technique was employed. The water level was defined at the top of the foundation level [2]. As we know, elastic modulus (E) is related to the confining pressure. In this research the value of elastic modulus (E) is decreased from bottom of dam body to the crest and shell surfaces, according to the confining pressure [1].

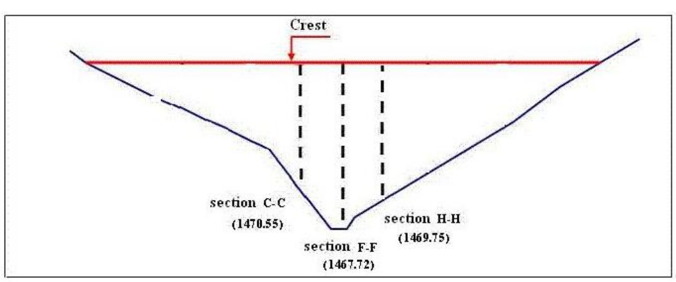

Figure 1 Schematic of longitudinal section of Bidvaz dam

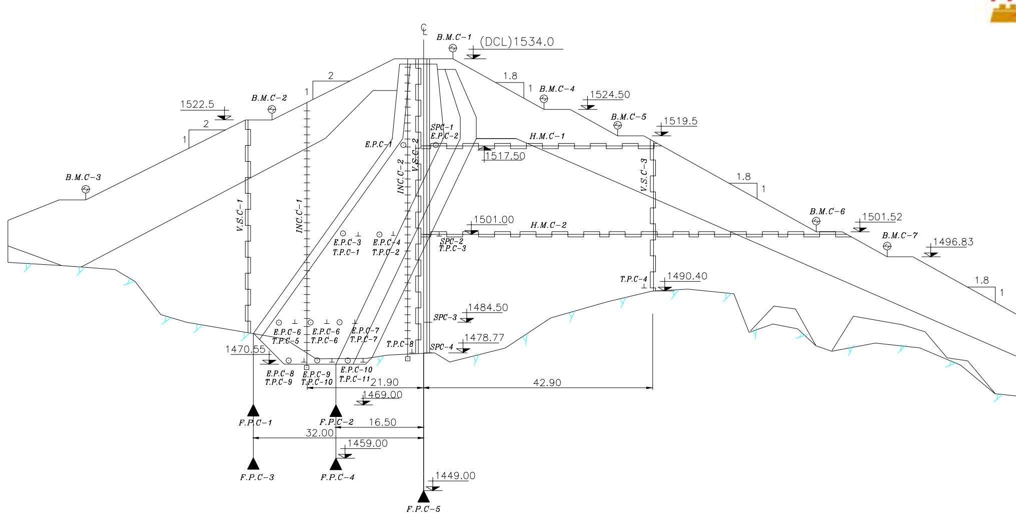

Figure 2a Instrumented cross- section (Section F-F) of Bidvaz dam

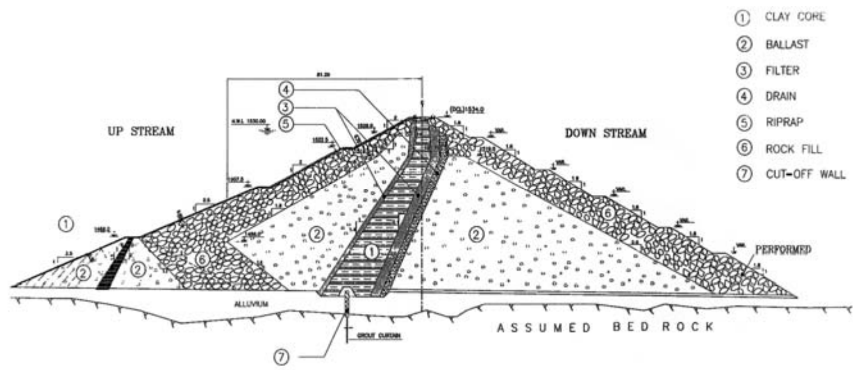

Figure 2b Highest cross-section (Section F-F) of Bidvaz dam

Table1. Foundation and dam body parameters, used in numerical analysis

Material	γ(kN/m3)	k (cm/s)	E (MPa)	ν	φ (°)	c`(kPa)	ψ(°)	Constitutive model
Core	17.6	1e-9	17	0.35	18	47	0	M-C
Shell	21	-	34.5	0.3	40	0	10	M-C
Filter	19	-	24	0.27	35	0	5	M-C
Drain	19	-	26.5	0.27	34	0	4	M-C
Rockfill	21	-	35.5	0.3	42	0	10	M-C
Foundation	20	1e-3	200	0.3	-	-	-	Elastic
Bed Rock	22.5	Not permeable	16000	0.25	-	-	-	Elastic

Key:

γ: *Unit Weight* — **E** *: Elastic Modullus*
k: *Permability* — **φ** *: Friction Angel*
c: *Cohesion* — **ν** *: Poissons Ratio*
ψ: *Dilaitancy Angel* — **M-C**: Mohr-Coulomb

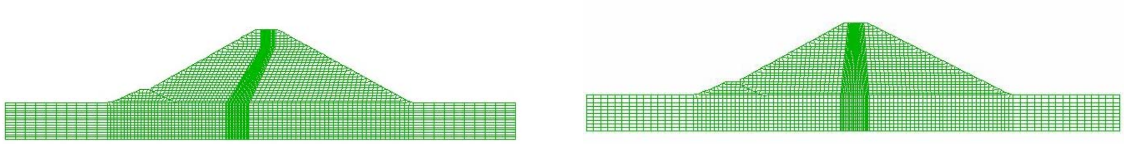

Figure 3 Finite difference mesh of the inclined core (Bidvaz) dam and the hypothetical vertical core dam

Figures 4 and 5 present respectively vertical and horizontal displacements for the Bidvaz dam (ICD) and the hypothetical dam with vertical core (VCD) at the end of construction. It can be realized that the maximum settlement occurs approximately at the mid height of the dam. The pore water pressures generated in the core at the end of construction is shown in Figure 6. For the inclined core dam, the maximum pore water pressure (300kPa) is developed in 22% of the dam height, and the maximum pore water pressure (410kPa) is developed in 1/3 of the dam height for vertical core dam. Some of the calculated values are presented and compared in Table 2.
Figures 7 and 8 show calculated and measured settlements for the instruments INCF-2 and INCC-1 for the Bidvaz dam. Also, INCF-1 instrument is damaged at section F-F. Therefore, a similar instrument at section C-C is used for comparison. There is a good agreement between the calculated and measured values. In Figure 8, there is a little difference between the calculated and measured values, because section F-F is higher than section C-C (Fig 1). A comparison between the calculated and measured pore water pressures in bottom of the core at section F-F is shown in Figure 9. Unfortunately, the instrument EPF-8 is damaged and we had to use similar instruments at section H-H and section C-C.

Figure 10 presents calculated vertical effective stress in the core center and two points at the upstream and downstream of the core. This Figure clearly demonstrates the effect of arching in the core. This comparison is made to show the development of arching phenomena within the dam body during construction of the dam. As expected, the stresses recorded in the core are lower than their associated γh; on the contrary, in the downstream filter the recorded stresses are higher than γh.
Another conclusion drawn from comparison of the two dams is that the shear stress at the upstream filter, specially in lower levels of the core in the inclined core dam is greater than the same value in the vertical core dam. The above conclusion is important for analyzing the upstream slope stability [5, 6].

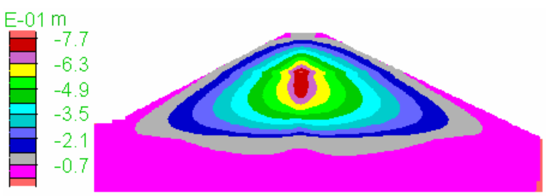

Figure 4aVertical displacement contours
at the end of construction (VCD)

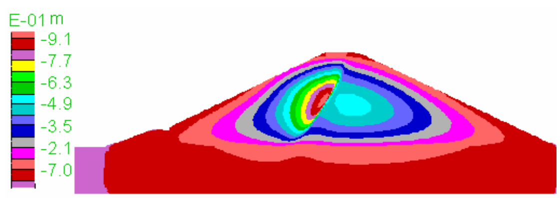

Figure 4b Vertical displacement contours
at the end of construction (ICD)

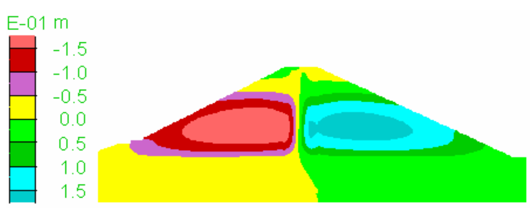

Figure 5a Horizontal displacement contours
at the end of construction (VCD)

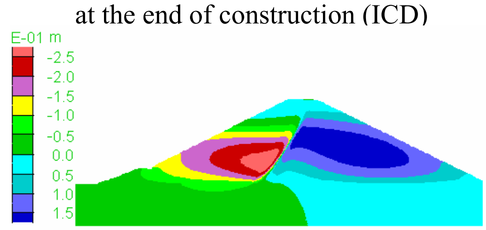

Figure 5b Horizontal displacement contours
at the end of construction (ICD)

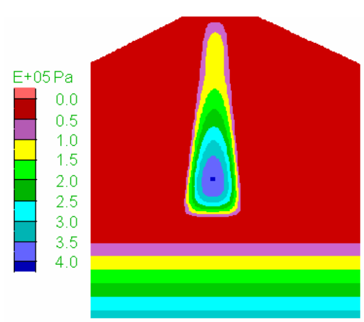

Figure 6a Pore water pressure contours
at the end of construction (VCD)

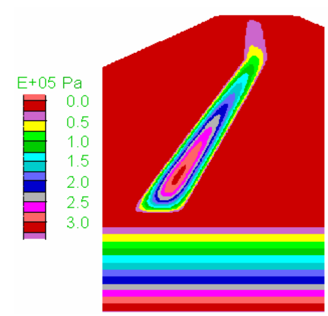

Figure 6b Pore water pressure contours
at the end of construction (ICD)

Table 2. The results of numerical analysis at the end of construction

Total stress at center of the core (bottom of the core level) (kPa)	Horizontal displacement (location)	Excess pore pressure (kPa) (location from bottom of the core,m)	Max Settlement (cm) (location from bottom of the core,m)	Dam Type
756	25 upstream shell	300 center of core ,15	93 30, near to downstream filter	Inclined core
870	15 downstream shell	410 22.5, center of the core	77 40, center of the core	Vertical core

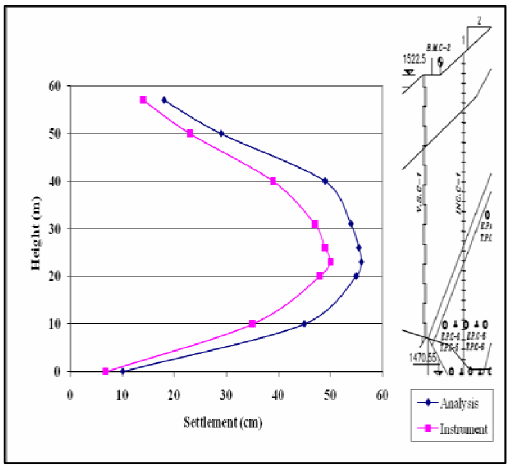

Figure 7 Comparison of numerical analysis settlement with instrument INCF-2

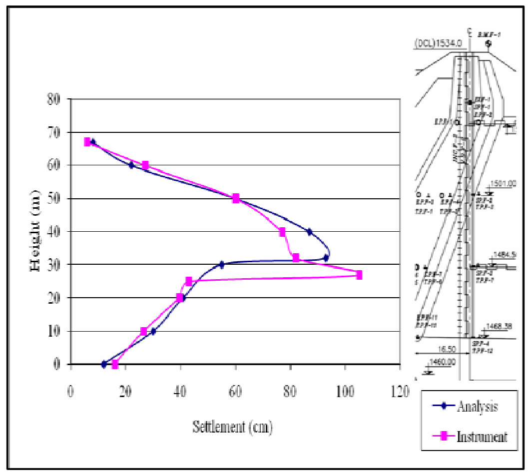

Figure 8 Comparison of numerical analysis settlement with instrument INCC-1

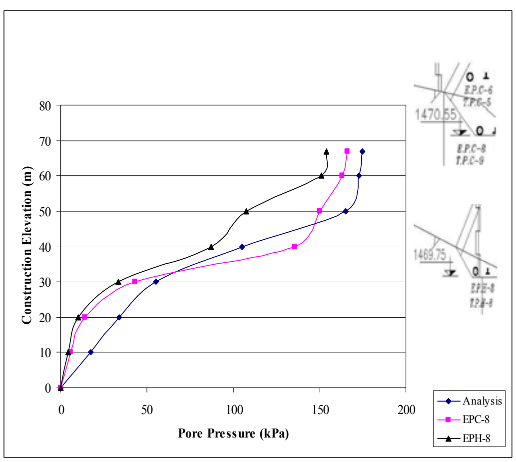

Figure 9 Variation of pore pressure at bottom of the core during construction. Comparison of numerical result and instrumentation

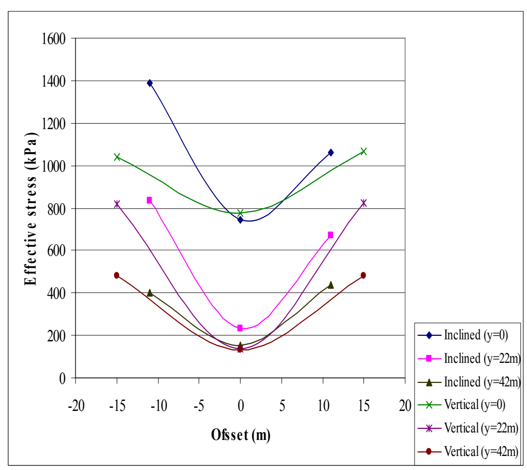

Figure 10 Variation of Effective stress across to the core at 3 different level. (y: Height from bottom of the core).

4.2. During Earthquake

In order to evaluate the behavior of both dams during earthquake, nonlinear dynamic analyses with the same mesh are carried out [5-6]. The seismic stability of the earth dams is evaluated with nonlinear displacement analysis, using the accelerograms obtained by ground response analysis. The scaled (to PGA=0.4g) and real accelerograms were used as input motions and introduced to the bedrock. More recently, dynamic analyses incorporating nonlinear, total-stress-based soil models have been used more frequently in engineering applications. The soil properties required for such analyses are generally similar to those currently used for approximate total-stress analyses.

Assumptions for the dynamic analysis:

-Earthquake occurs at the end of construction.
- Total stress analysis without pore pressure calculation is carried out
-Before starting dynamic analysis, all of the static deformations are reset to zero
- Free-field for boundary condition. [5, 6, 7]

-For estimating dynamic parameter for dam body and foundation, the following equations is used:

$$G_{\max} = \frac{625}{(0.3 + 0.7e^2)}(Pa)^{0.5}(OCR)^n(\sigma'_m)^{0.5} \qquad (1)$$

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

Pa: atmospheric pressure
σ'_m: average effective stress
e: core material void ratio
OCR: over–consolidation ratio

-Reyligh ratio=2% in order to consider damping effect [4].

As for the earthquake input, TABBAS earthquake time history (1978) is employed (Fig 11). The pick ground acceleration (PGA) is 0.9g. For the stability analysis, the PGA is scaled to 0.4g and filtered for a maximum frequency of 15 Hz.
After completing the dynamic analysis, we used the computed deformations for comparison of the behavior of the two dams. Figures 12 and 13 present respectively contours of the vertical and horizontal displacements after the earthquake for PGA=0.4g. Generally, there is an obvious difference in the contours of displacements for the two dams.

Figures 12a and 12b show that in the inclined core dam, the maximum settlement occurs in the upstream side of the crest; while in the vertical core dam, the maximum settlement is in the crest center. It is obvious that the settlements in the vertical core dam are mostly limited to the core. However, in the inclined core dam, the settlement contours are more concentrated in the upstream shell. Figures 13a and 13b show contours of the horizontal displacements after the earthquake shaking. Also, this figure indicates that the horizontal displacements are symmetric with respect to the dam centre line in the vertical core dam. It is obvious that the maximum horizontal displacement occurs in the surface of the shell. The maximum horizontal displacement in the dam with inclined core is greater than the same value in the vertical core dam.

Figures 14 and 15 present respectively the time history of the dynamic horizontal and vertical displacements of the crest level. It can be realized that rapid changes occur approximately at the time of 11sec. The residual horizontal and vertical displacements are 20 and 40 cm respectively, in the inclined core dam; while, in the vertical-core dam, the residual horizontal and vertical displacements are respectively 5 and 30 cm. The dynamic analyses were repeated for both of the dams with PGA 0.7g, 0.8g, and 0.9g. The results of the analyses in terms of stability/instability at the end of shaking, maximum settlements, and maximum horizontal displacements are summarized in Table 4. It can be seen that for PGA=0.9g, the two dams are unstable; for PGA=0.8g, only the dam with inclined core is unstable; and for PGA=0.7g and 0.4g, both of the dams are stable [1].

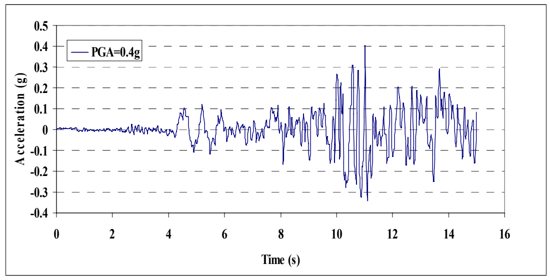

Figure 11 Tabbas Horizontal Accelograph (1978)

Figure 12a Vertical displacement profile after earthquake (ICD)

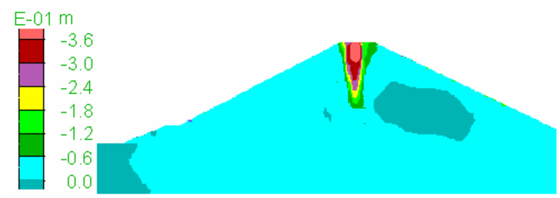

Figure 12b Vertical displacement profile after earthquake (VCD)

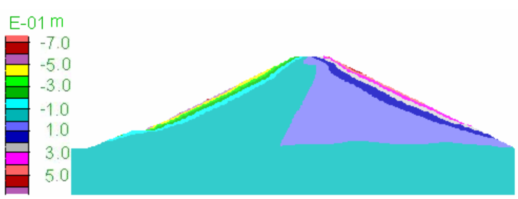

Figure 13a Horizontal displacement profile after earthquake (ICD)

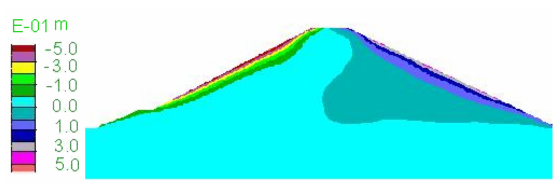

Figure 13b Horizontal displacement profile after earthquake (VCD)

Table 4. The results of dynamic numerical analysis after earthquake.

Max. horizontal displacement (D/S) (m)	Max. horizontal displacement (U/S) (m)	Max settlement (m)	Stability/ Instability	Max acceleration	Dam Type
-	-	-	instable	0.9g	Inclined core
-	-	-	instable	0.9g	vertical core
-	-	-	instable	0.8g	Inclined core
1.7	2	1.86	stable	0.8g	vertical core
1.75	2.35	1.92	stable	0.7g	Inclined core
1.5	1.65	1.52	stable	0.7g	vertical core
0.61	0.76	0.43	stable	0.4g	Inclined core
0.52	0.55	0.37	stable	0.4g	vertical core

5. CONCLUSION

In this paper, the during-construction and seismic behavior of the Bidvaz dam with inclined clay core was studied. The behavior of this dam was compared with the behavior of a similar dam, however, with a vertical clay core, by means of numerical analyses. FLAC 2D software was employed for the analyses of the dam during the construction stage and earthquake excitation. The clay core, rockfill, and filters are modeled using the Mohr-Coloumb elasto-plastic behavior. The static analysis is performed by an effective stress approach and the dynamic analysis is performed by a total stress approach. For the simulation of earthquake shaking, the Tabbas accelograph (1978) is used and scaled to PGA of 0.4g, 0.7g, 0.8g, and 0.9g.

Static Analysis: The maximum horizontal and vertical displacements at the end of construction in the dam with inclined core are greater than the associated displacements in the dam with vertical core. At the end of construction, the maximum pore water pressure value in the vertical core is greater than the associated value in the inclined core.

Dynamic Analysis: The sensitivity analysis using four values of PGA showed that the dam with inclined core is generally less stable than the vertical core dam. In the inclined core dam, the instability occurs at the upstream shell. The maximum settlement in the vertical core dam occurs at the center line of crest. But, the maximum settlement in the inclined core dam occurs at the upstream part of crest. The maximum settlement of the shell in the inclined core dam is greater than the one in vertical core dam. The maximum horizontal displacement in the upstream shell in the inclined core dam is greater than similar displacement in the vertical core dam.

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REFRENCES

1. Karbor-e-shyadeh, A. H. (2007). Numerical Analysis of Earth dams with Inclined Core, Subjected to Earthquake Loading (Case-study:Bidvaz Dam). Msc Thesis; Amirkabir University of Technology, Iran
2. ITASCA Consulting Group, (2001). “Fast Lagrangian Analysis of Continua-FLAC Code’s technical manuals”
3. Toosab Company, (2004). Bidvaz dam Report.
4. Seed, H. B.and Idriss, I.M. (1970). Soil moduli and damping factors for dynamic response analyses. *Earthquake Engineering Research Center*, **EERC**, 79-10, Universityof California, Berkeley, USA
5. Gazetas, G. and Dakoulas, P. (1992). Seismic analysis and design of rockfill dams, state of the art, *Soil Dynamics and Earthquake Engineering*, **11**, P 27-61.
6. Ozkan, M.Y. (1998). A review of considerations on seismic safety of embankments, earth and rock-fill dams. *Soil Dynamics and Earthquake Engineering*, **Vol. 17**, pp 439-458
7. International Commission on Large Dams, ICOLD (1986). Earthquake Analysis for Dams, state of the art, ICOLD, **Bulletin n52**, Paris, France.