Determination of Excess Pore Pressure in Earth Dam after Earthquake

S.M. Nasrollahi

Faculty of Islamic Azad University – Qaenat Branch, Qaen, Iran.
Email: s.m.nasrollahi@gmail.com

ABSTRACT:

Pore pressure within the core of the embankment dams play a decisive role in performance of the earth dams. Although it may be high during the construction stage of the dam, it will be dissipated to a reasonable level as the consolidation process of the core is progressing in the long term. However, if these dams experience heavy earthquakes in short time, the rapid increase of the pore pressure may put the dam at risk in some critical conditions. In this paper the Excess pore pressure development of the Karkheh large embankment dam during the earthquake loading has been investigated. The Karkheh Dam is the largest storage dam in Iran that has been recently constructed in the south-west of the country. This is an earth dam by a mixed clay core. The length of the dam crest is 3030 m and its maximum height at the river section is 127 m. In the analyses carried out in this study, the FLAC-2D was used. To prepare the initial requirements for doing the dynamic analyses, the dam was modeled from the beginning of the construction. Different construction stages and also the impounding stages of the dam were modeled by 32 stages from the beginning of the dam construction up to Dec.2004. After application of the selected accelerogram to the model and doing the dynamic analysis, considerable changes happen both in values and in the pattern of the pore pressure developments. The results of the dynamic analyses revealed that the value of the developed pore pressure at the mid. Levels of the core increases and its distribution pattern changes during an earthquake.

KEYWORDS:
Karkheh Dam, Mixed clay core, non-linear dynamic analysis, pore pressure, earthquake.

1. INTRODUCTION

The Karkheh Dam is the largest storage dam in Iran that has been recently constructed in the south-west of the country. This is an earth dam by a mixed clay core. The length of the dam crest is 3030 m. and its maximum height at the river section is 127 m. The width of the dam is 12 m. at the crest and 1100 m. at the widest point at the foundation level. The Karkheh dam has been built on an alluvium consisting of alternative layers of conglomerates and mudstones. To monitor the performance and behavior of the dam during construction and also in long term utilization, a comprehensive instrumentation system consisting of more than 1000 different devices has been designed and performed [1], [2], & [3]
It is of great importance to control and monitor the stability of the dam at different loading conditions [4], & [5]. One of the most critical conditions is when the dam experiences the earthquake loading. This kind of loadings due to uncertainties in magnitude and its occurrence time may cause some serious problems for dams. The exact response of an earth dam during an earthquake loading is not clear. Many factors such as dam characteristics, site conditions, and earthquake loading specifications highly affect the dynamic responses of the dams. The non-elastic and non-linear behavior of the soil materials, extensively influence the dam responses. While the dam usually behaves elastic during small dynamic waves, they may totally move to the plastic ranges when are subjected to heavy earthquake loadings.
In this study the pore pressure development within the core of the Karkheh dam during the earthquake loading is investigated and evaluated. The FLAC finite difference package has been used to model and carry out the dynamic analyses [6]. This is a 2D package for modeling earth structures which is capable of analyzing the soil-water interaction under earthquake loadings [7]. To verify the analyses results, the dam first has been analyzed under static conditions using the field data measured from different instruments in the site. Then, taking into account the seismicity studies of the region, an appropriate accelerogram has been selected and applied to the

model to do the dynamic analyses and to estimate the pore pressure development within the core of the dam during the earthquake loading.

2. THE NON-LINEAR DYNAMIC ANALYSIS

The equivalent linear analysis is one of the common methods to evaluate the dynamic behavior of the earth structures. In this study, first a linear analysis has been done using the initial values of the damping ratio and shear modulus. Then considering the maximum value of the shear strain, and using the laboratory curves, the new values of damping ratio and shear modulus are estimated [8]. These values are used to do the new analysis. This procedure is repeated several times until no variation happens in the material properties. In the non-linear analysis which has been used in this study, the non-linear stress-strain relationship is followed directly by each element. The damping ratio and shear modulus of the materials at different strain levels are calculated automatically in this method. This method needs a comprehensive stress-strain model to estimate the dynamic behavior of the material.

2.1 The Hysteretic Stress-strain Behavior in Shear

The real behavior of soils is non-linear and hysteretic under cyclic loadings. This behavior can be simulated by the Masing model (1926), which is capable of modeling the dynamic behavior of the soils. The shear behavior of the soil, in this model, may be explained by a backbone curve in form of $\tau = F_{bb}(\gamma)$ in which the F_{bb} is as below [9]:

$$F_{bb}(\gamma) = \frac{G_{\max}\gamma}{1+(G_{\max}/\tau_{\max})|\gamma|} \tag{2.1}$$

The stress-strain curve follows the backbone curve in the first loading, but to explain the unloading-reloading, the above equation has to be modified. If the stress returns from point (γ_r, τ_r), the stress-strain curve follows the path below:

$$\frac{\tau-\tau_r}{2} = F_{bb}\left(\frac{\gamma-\gamma_r}{2}\right) \tag{2.2}$$

In other word, the unloading-reloading curves have the same shape as the backbone curve except the fact that its origin is displaced towards the stress returning point and they have been magnified by the ratio of 2. The value of $\frac{G_{\max}}{\tau_{\max}}$ ratio depends on the void ratio (e), initial effective stress $(\bar{\sigma}_v)$, and the plastic index (PI). This value can be determined from the table given by Hardin & Drnevich [10].

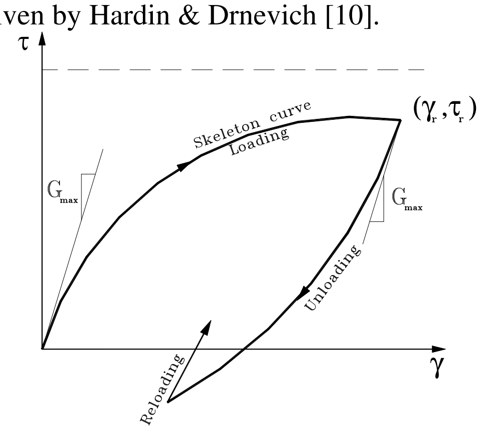

Figure 1 The general pattern of loading and unloading of the soils

The Masing rules (1926) seem not to be enough to explain the soil responses under general cyclic loading. Finn et al., (1976), developed some rules to describe the irregular loadings.
They suggested that the new unloading and reloading curves follow the two rules presented below:

I- If the new unloading or reloading curve exceeds the last maximum strain and cut the backbone curve, it will follow the backbone curve till reach to the next retaining point (figure2-a).

II- If a new unloading or reloading curve passes through the previous unloading or reloading curve, it will follow the former stress-strain curve (figure 2-b).

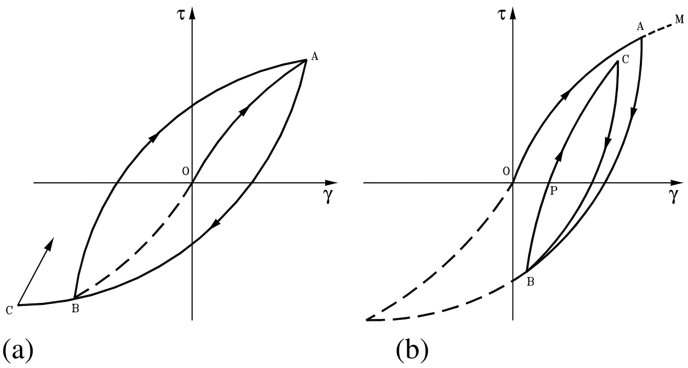

Figure 2 The modified Masing rules [11]

According to this model, the tangent shear modulus can be defined as below at a point on the backbone curve:

$$G_t = \frac{G_{\max}}{\left(1 + \frac{G_{\max}\left|\gamma\right|}{\tau_{\max}}\right)^2} \tag{2.3}$$

The tangent shear modulus, at a point on the new reloading- unloading curve can be also defined by the following equation:

$$G_t = \frac{G_{\max}}{\left(1 + \frac{G_{\max}}{2\tau_{\max}}\left|\gamma - \gamma_r\right|\right)^2} \tag{2.4}$$

Based on the research results, as the load cycle increases, the shear stress decreases, which mean the shear stress-strain curves, get more inclined. Lee et al. (1999) showed that in spite of decreasing in shear modulus by increasing the number of load cycles, the shear modulus is almost constant within the range of number of cycles that happen during earthquake.
The maximum shear modulus can be estimated using the existing empirical equations. For cohesion soils it may be determined from the following equation, suggested by Seed & Idriss:

$$G_{\max} = 625\ F(e)\ (OCR)^k\, P_a \left(\frac{\sigma_m}{P_a}\right)^n \tag{2.5}$$

Where;
OCR= overconsolidation ratio
K= coefficient related to the soil plastic index (PI)

σ_m = mean effective principal stress

n = stress power, usually equal to 0.5

F(e) = is a function from void ratio (e), and can be obtained from different empirical equations. Among them one has been suggested by Hardin (1978) is as follows:

$$F(e) = \frac{1}{(0.3 + 0.7e^2)} \tag{2.6}$$

Also the maximum shear modulus for granular materials can be estimated from Seed et al. (1986) equation:

$$G_{\max} = 21.7 P_a K_{2\max} \left(\frac{\sigma'_m}{P_a} \right)^{0.5} \tag{2.7}$$

The $K_{2\max}$ is related to the type and density of the soil and can be determined from the relative density of the soil material.

3. DYNAMIC ANALYSIS OF THE KARKHEH DAM

In the analyses carried out in this study, the FLAC-2D was used. It is finite difference computer software capable of modeling many soil phenomena such as seepage, consolidation, and analyzing different dynamic responses of geotechnical structures under plane-strain conditions. In this model, the motion equations are derived in a continuum media. In this program the motion equations are used to obtain the new velocities and displacements from existing stresses and forces. The strain rates are then calculated according to the new nodal velocities in each element. In this program all equations mentioned so far are solved by means of finite deference.

To do the analysis of the dam, it is required to select a typical or a critical section of the dam. In this study the critical section has been selected in a way that if the dam stability is met in this section, no other section will be unstable in the same condition. Taking into account all sections of the Karkheh dam from different aspects such as their base elevations, the height of the filling, the depth of the river, the induced settlements, and the pore pressure developments in them, the section 5-5 of the dam which is located at the station 1+230 km. would be the dam critical section. Therefore, this section has been concentrated upon in this study which is shown in figure (3).

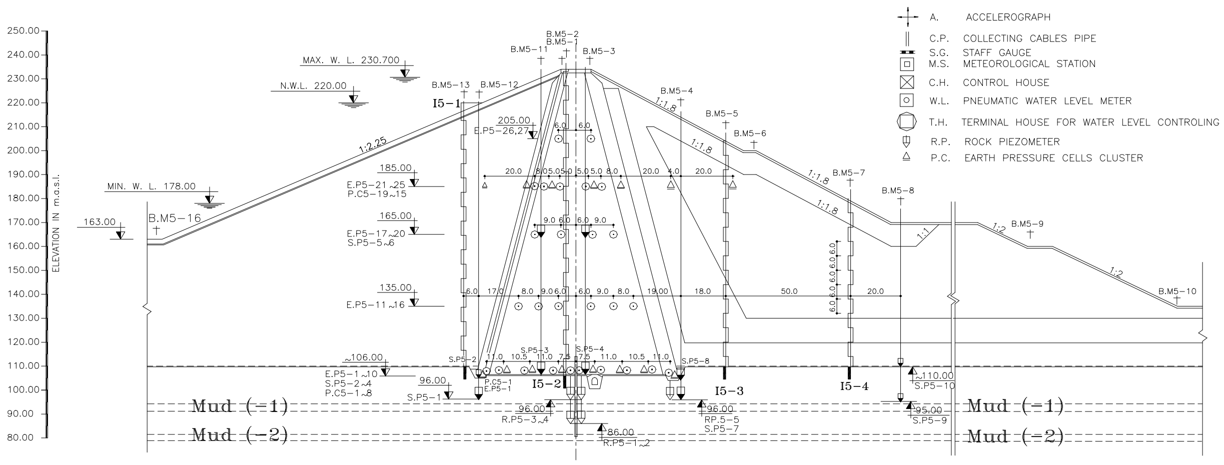

Figure 3 The critical section of the Karkheh Earth Dam with the ground profile and position of the installed instruments (Sec.5-5 at station 1+230 km.).

The modeling zone covers dam body and cofferdam together with a part of the dam foundation down to 70 m. depth and 250 m length on both sides of the dam axis. To model the dam a mesh of 23x80 has been used. To model the stage construction, the dam body has been divided into 5 m. layers. Due to concentration of this study on the pore pressure developments within the dam core, and also the sensitivity of this zone, the selected mesh in the core had smaller grids, so that 20 elements were put in the core width.

4. THE STATIC ANALYSIS

To prepare the initial requirements for doing the dynamic analyses, the dam was modeled from the beginning of the construction. Considering the layer construction of the dam and consequent changes happen in the material properties as the filling of the dam increases, the Duncan-Chang non-linear model with Mohr-Coulomb yielding surface was used to model the shell and core materials. The foundation materials were modeled using Mohr-Coulomb criterion.
Different construction stages and also the impounding stages of the dam were modeled by 32 stages from the beginning of the dam construction up to Dec.2004. Doing some back analyses and comparing the numerical results with field data obtained from the instrumentation system, the input parameters of the dam were verified and the numerical model was calibrated as an important procedure prior to dynamic analyses.

5. THE DYNAMIC PROPERTIES OF THE MATERIALS

The results of the static analyses were used to provide the initial requirements of the dynamic analyses. In this regard, the Masing model, with the Mohr-Coulomb yielding surface was used to model the behavior of the core and shell materials of the dam. The foundation materials were considered to behave linear that seems to be true due to their different nature and stiffness compared with the dam body materials. To estimate the maximum shear modulus, the suggested equation for granular soils was used since in the Karkheh dam the core material is mixed clay with 40 % sands and gravels. The different parameters used in the dynamic analyses are shown in tables 1 and 2.

Table 1 The dynamic parameters and equations used for the filter and foundation materials.

Filter materials		Foundation	
$G_{\max}$	G_t	$V_{s\,(km/s)}$	$G_{\max}$
$21.7\,P_a\,(50)\left(\dfrac{\sigma_m}{P_a}\right)^{0.5}$	$0.7G_{\max}$	1	$\rho V_s^{\,2}$
G_t Has taken constant since its variations during cyclic loadings have been small and negligible.			

Table 2- The dynamic parameters and equations used for the core and shell materials

parameters	n	$G_{\max}$	PI	γ_r'	G_t	
					Backbone curve	Unloading-reloading curve
Mixed clay core	.34	$21.7\;P_a(40)(\dfrac{\sigma_m}{P_a})^{0.5}$	15	$7.7\times10^{-7}\sqrt{\sigma_v}$	$\dfrac{G_{\max}}{\left(1+\dfrac{G_{\max}\lvert\gamma\rvert}{\tau_{\max}}\right)^2}$	$\dfrac{G_{\max}}{\left(1+\dfrac{G_{\max}}{2\tau_{\max}}\lvert\gamma-\gamma_r\rvert\right)^2}$
coarse shell material	.25	$21.7\,P_a\,(130)(\dfrac{\sigma_m}{P_a})^{0.5}$	0	$6\times10^{-7}\sqrt{\sigma_v}$		

6. THE INPUT ACCELERATION

To evaluate the seismic parameters of the Karkheh site, the seismic risk analyses have been carried out. According to the performed seismic studies on the basis of probabilistic seismic hazard analysis (PSHA), the specifications of the design based earthquake (DBE), for the Karkheh Dam site are recommended as below [12],

- Maximum design acceleration: 251 cm/sec.2 = 0.256 g
- Maximum design velocity: 23 cm/sec.
- Maximum design displacement : 15 cm

Comparing the above parameters with those belong to different recorded earthquake occurred in Iran, the Deyhook accelerogram by the record No. 1082-1 was found to be the most similar to the Karkheh site seismic parameters, thus it was selected for the dynamic analyses in this study. To optimize the analyzing time and prevent the divergence of the numerical results, the first 15 sec. of the accelerogram was used and the frequencies more than 5 Hz. Were omitted. The acceleration was applied to the base of the model which was considered at the depth of 70 m. from the ground surface.

7. THE EVALUATIONS OF THE PORE PRESSURE WITHIN THE CORE OF THE KARKHEH DAM DURING EARTHQUAKE

After application of the selected accelerogram to the model and doing the dynamic analysis, even for the case when there is no seepage flow in the core and the flow analysis mode of the model is off, considerable changes happen both in values and in the pattern of the pore pressure developments (figures 6 and 7). The maximum pore pressure value in this case reaches to 1043 kPa. Which 26% greater than that is of exist in the core before earthquake. It can be seen in figure 7 that the more we move towards the high levels, the more influences of the earthquake loading happen within the core.
Also it is quite evident that at the same level in the core, the more we move towards the sides and filter zones, the more decrease occur in the pore pressure. This may be attributed to the lateral expansion of the core under constant volume and undrained condition due to the vertical displacement and settlement of the core during the earthquake loading. Thus, the pore pressure dissipation happens considerably near the core boundary zones.

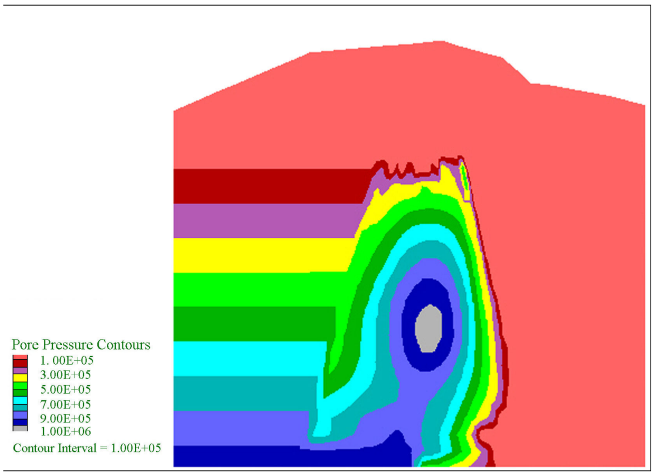

Figure 5 The pattern of pore pressure development after earthquake

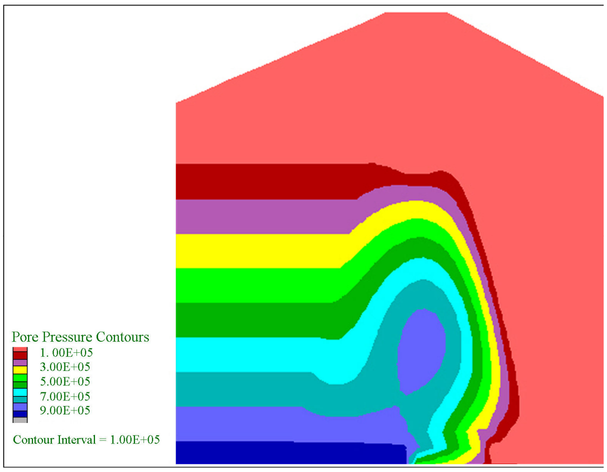

Figure 4 The pattern of pore pressure development before earthquake

The trend of the pore pressure variations during the earthquake loading in the central zones of the core at different levels have been shown in figure 8 to 11. The selected points are so that they can show the amount of the pore pressure developed at the position of the electrical piezometers EP5-3, EP5-12, EP5-18, and EP5-23 installed at different levels of the sec. 5-5 of the dam.

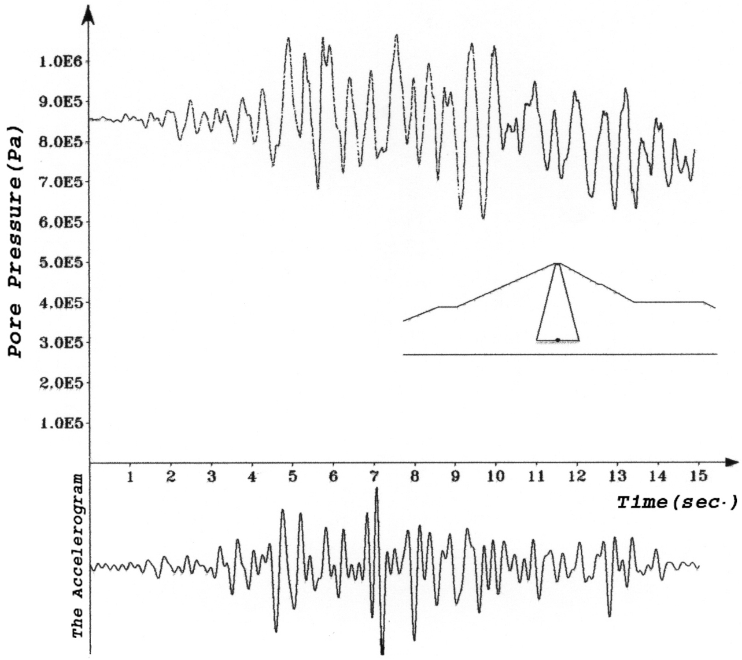

Figure 6 Variation of the pore pressure at the position of the EP5-3 (elevation of 106), in the core due to earthquake loading estimated from numerical analyses.

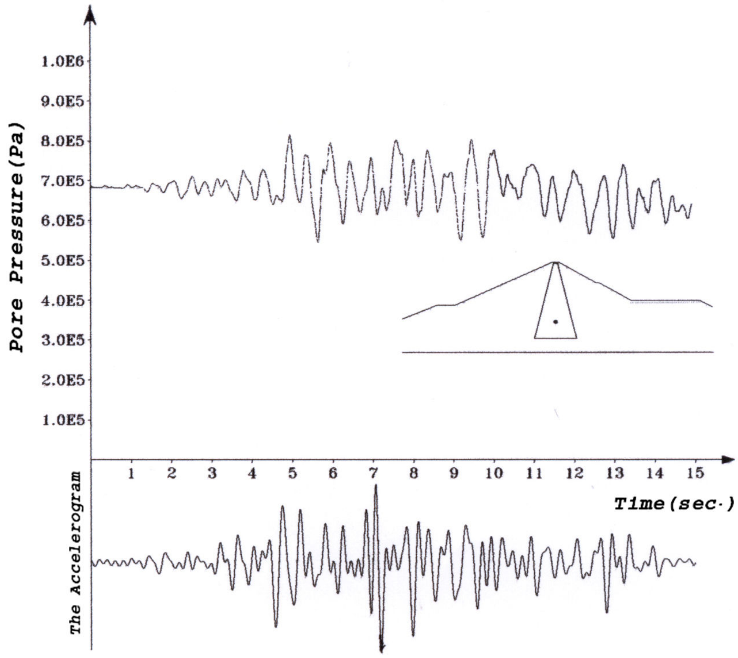

Figure 7 Variation of the pore pressure at the position of the EP5-12 (elevation of 135), in the core due to earthquake loading estimated from numerical analyses.

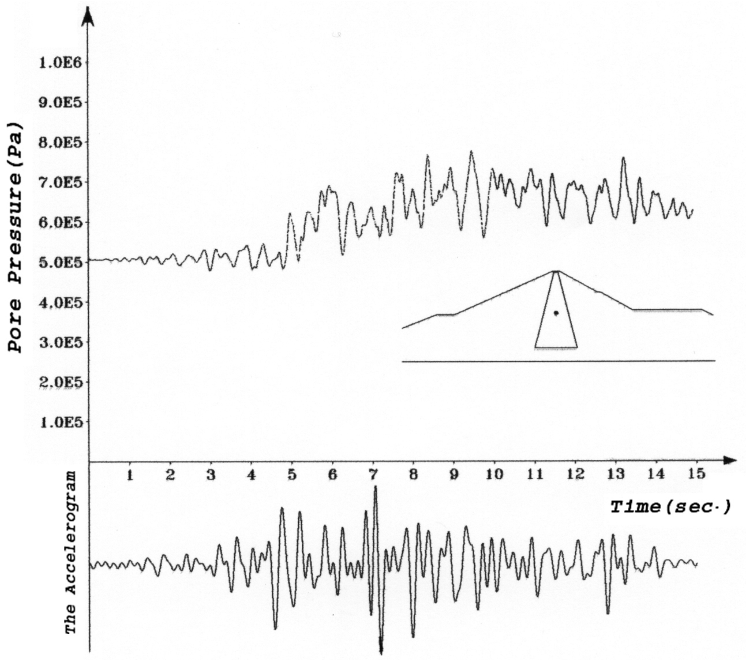

Figure 8 Variation of the pore pressure at the position of the EP5-18 (elevation of 165), in the core due to earthquake loading estimated from numerical analyses.

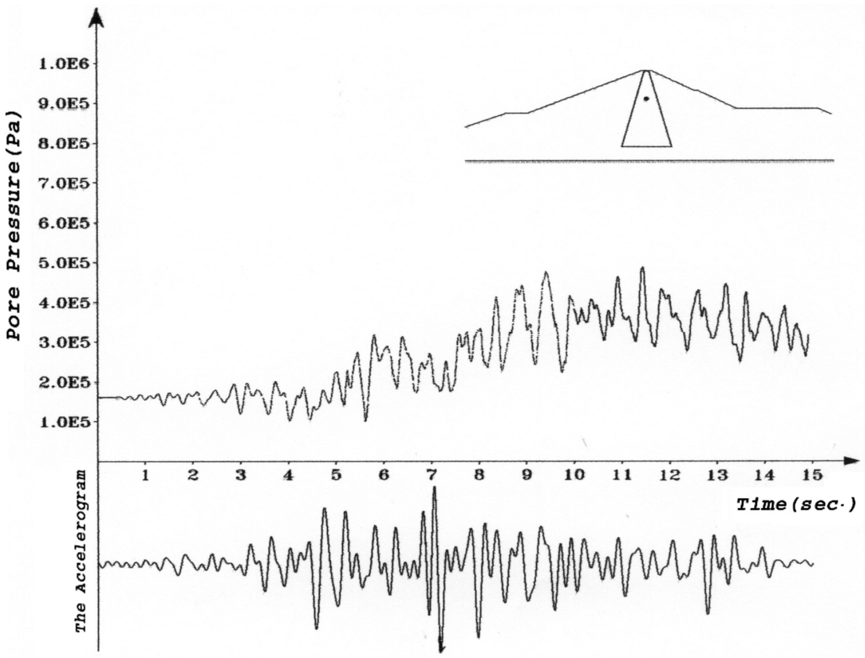

Figure 9 Variation of the pore pressure at the position of the EP5-23 (elevation of 185), in the core due to earthquake loading estimated from numerical analyses.

Another important factor that plays a decisive role in the stability of the core of the earth dams is the pore pressure ratio (Ru), which is defined as the ratio of the induced pore pressure to the total soil pressure. In this case if the Ru as a direct index of the core stability reaches to 1, it means that the effective stress is becoming negligible and the risk of the hydraulic fracturing of the dam is very high at that point.
According to the dynamic analyses results, the pore pressure ratio at the point that maximum pore pressure had been developed was estimated. It was found to be 0.72 which is well below 1. Also the maximum total soil pressure was 1241 kpa which is greater than the induced pore pressure (1043 kpa) at this point. As a result, it can be concluded that during the design earthquake there is no possibility of hydraulic fracturing or soil piping

inside the core of the Karkheh dam. To show the amount of Ru during earthquake loadings at different levels of the core, its variations versus time are plotted in figures 12 to 15.

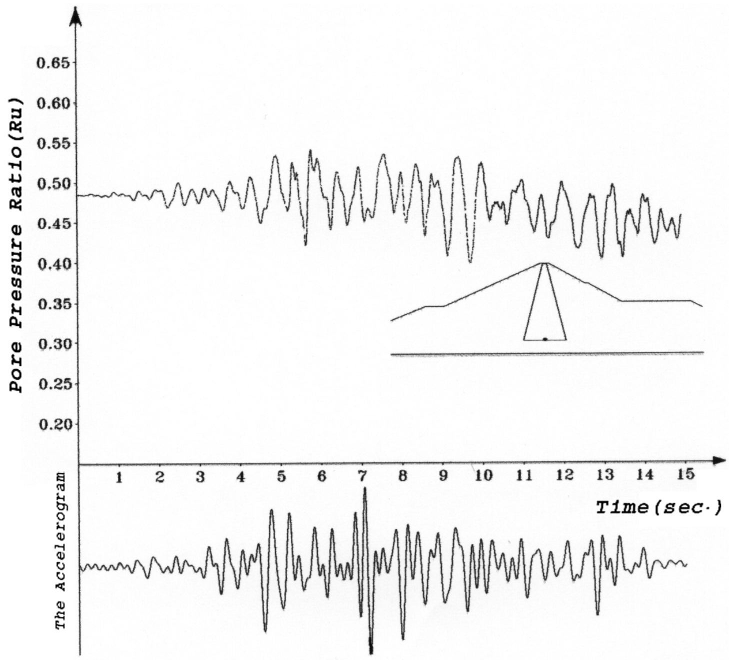

Figure 10 Variation of the pore pressure ratio (Ru), at the position of the EP5-3 (elevation of 106), in the core due to earthquake loading estimated from numerical analyses.

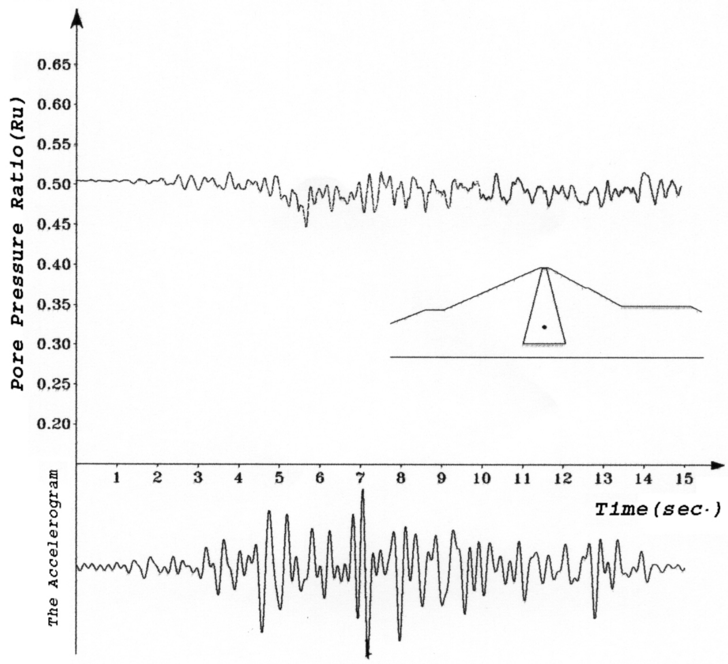

Figure 11 Variation of the pore pressure ratio (Ru), at the position of the EP5-12 (elevation of 135), in the core due to earthquake loading estimated from numerical analyses.

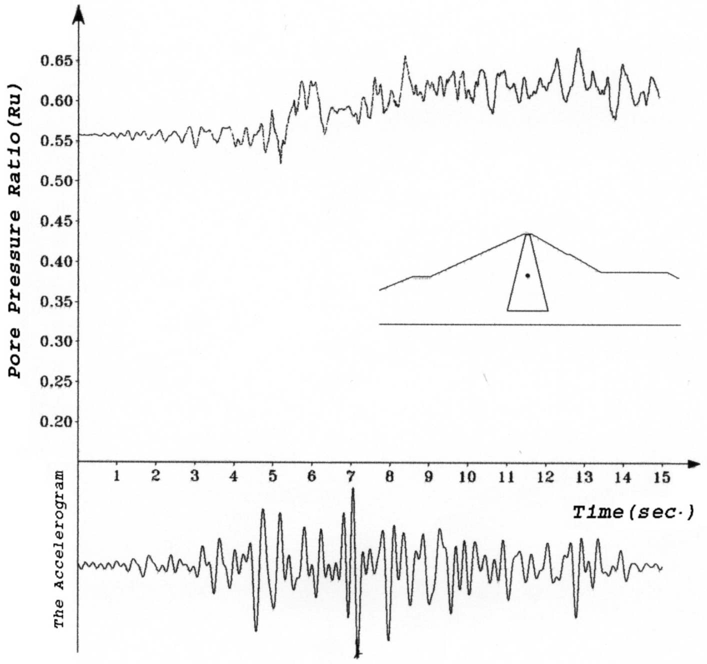

Figure 12 Variation of the pore pressure ratio (Ru), at the position of the EP5-18 (elevation of 165), in the core due to earthquake loading estimated from numerical analyses.

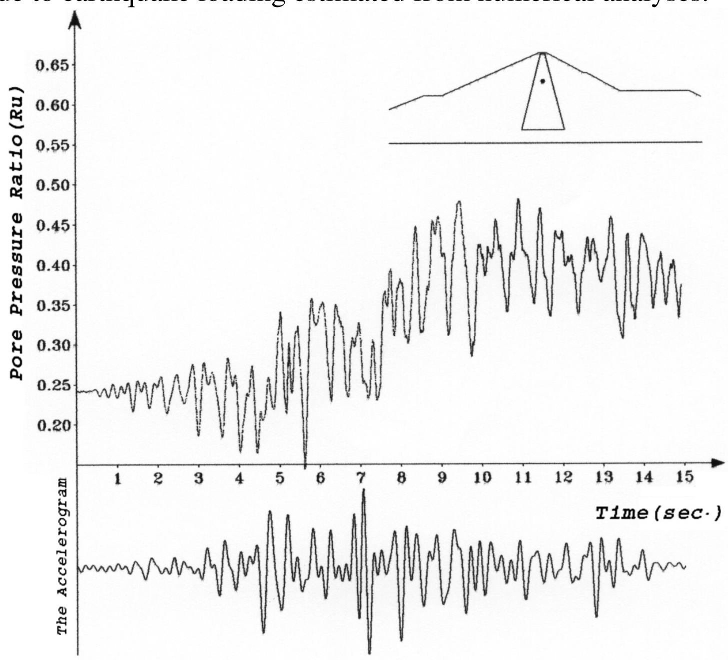

Figure 13 Variation of the pore pressure ratio (Ru), at the position of the EP5-23 (elevation of 185), in the core due to earthquake loading estimated from numerical analyses.

8. SUMMARY AND CONCLUSIONS

The response of the Karkheh large embankment dam with mixed clay core, under earthquake loading was investigated and evaluated. The FLAC 2-D finite difference package was used to model the dam and to do the dynamic analysis numerically. The input parameters were justified and the model was calibrated using the field data obtained from the regular measurements of more than 1000 instruments installed in the dam. The Deyhook accelerogram which is the most similar to the DBE motions of the Karkheh dam was selected and applied to the model. The pore pressure development within the core during earthquake loading was studied and calculated by the numerical model. According to the obtained results, the main following points can be concluded:

- The pore pressure developments move towards the higher levels of the core in comparison with those developed in the lower levels under static conditions. The maximum value of the pore pressure happens at the middle level of the core.
- At the same level within the core, the pore pressure decreases as moving towards the filter zones in the sides of the core.
- The maximum increase in the pore pressure during the earthquake loading is about 26% of the one that developed before the earthquake.
- The pore pressure ratio, Ru, increases to about 72% at the point which the maximum pore pressure induces during the earthquake loading. It means that the mixed clay core of the Karkheh large embankment dam shows satisfactory behavior if an earthquake similar to Deyhook occurs in the site.

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