Investigation of Seismic Behavior of a Clay Core Rock fill Dam Using Finite Element Method

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ABSTRACT

Clay core rock-fill (CCR) dams are chosen dam construction model due to their low cost and rapid construction advantages. The stability of dam embankment and analyzing their earthquake resistance is of great concern to geotechnical engineers. Here, we analyze static and dynamic degrading behavior of a clay core rock-fill (CCR) dam through using the finite element method. The static part of the analysis considers the stage construction, reservoir impoundment and total displacements while, the dynamic part considers the seismic response of the dam under a real earthquake data which the data corresponds to typical measures of a peak ground acceleration (PGA). The static state analyses show a gradual increase in the magnitude of vertical displacements during the impounding stage where the hydrostatic force acts on the surface of the dam body and causes additional force on the clay core section. When the dam is subjected to real earthquake data which had a 0.4 g PGA, we observe larger displacement values compared to the static phase.

Keywords: Clay core rock fill (CCR) dam, Earthquake, Finite element method, Static-dynamic analysis.

INTRODUCTION

All civilizations always need water supply for drinking, cleaning, farming, livestock fattening, irrigation, electricity and other basic needs from the earliest age until now. For this purpose, people have tried to settle around water supplies and they have preferred to live in those places or preferred to build huge water storages like dams, so far. Due to its economical reasons and easy applications, the use of clay-core rockfill (CCR) dam is a preferred model. However, high dams which have large water reservoir impoundment behind itself, include risks to the public, especially for large urbanizations (USCOLD, 1992). In order to investigate these risks, finite element (FEM) technique is one of the practical tools used in modelling dam's structural behaviour under static and dynamic loading.

Several researchers have used FEM technique in modelling of various types of dams. Westergaard (1933) proposed one of the earliest results of the effect of reservoir on the dam based on ; "Water is incompressible and dam is rigid with a vertical face" approach. Fenves and Chopra (1985) studied the seismic response of a dam by means of absorbing boundary conditions. Later studies have shown the importance of FEM modelling (e.g. Siyahi and Aslan, 2008a; Ghaedi et al., 2013; Afiri and Gabi, 2017; Sunbul, 2017). Rashidi et al. (2017) assessed the behavior of rockfill dams during construction and initial impoundment using numerical modeling and instrumentation data. In fact, studying clay core rock fill dam is difficult as it contains cut-off walls between different layers therefore the stress distribution between those layers, is also very complex during dynamic loading (ie. Liu et al. 2016).

Stability is a key factor in understanding the physical problems in engineering work. In terms of stability, numerical modelling provide us significant results in geotechnical problems. By using modelling technique, the evolution of static loading due to the gravity force during the construction phase and seismic loading under a strong ground motion data due to real earthquake, can be assessed. The determination of earthquake ground motions is one of the other important factor in terms of seismic safety of a dam. Since it is almost impossible to predict the seismic hazard of a given region, geotechnical engineers consider the maximum intensity which would be confronted during the life time of a structure, in their structural seismic response models.

In this study, we present a 2D FEM numerical analyses of both static and dynamic behaviour of a clay core rockfill dam. Results are presented in two steps, at first we consider static analyses which involve layered construction and predicted displacements; secondly, in order to assess the seismic behaviour of the dam, a real earthquake data set is used.

MATERIALS AND METHODS

Modelling

The finite element software Plaxis 2D, which has been developed for giving solutions to the geotechnical problems, was used throughout the analyses. The hardening soil model, using the theory of plasticity rather than the theory of elasticity, was implemented by Schnaz et al. (1999) and followed by a modification of the hyperbolic model proposed by Duncan and Chang (1970) and Duncan et al. (1980), used in the analysis. In this soil model, two hardening mechanisms (isotropic and deviatoric cases) are responsible for the deviation of stress paths (see also Schanz et al. 1999).

The example model, used in the analyses, is assumed as 35 m in height. This dam has a crest length of 225 m and a crest width of 10 m. It was considered to store 638.000 m^3 of water at maximum capacity (Fig. 1).

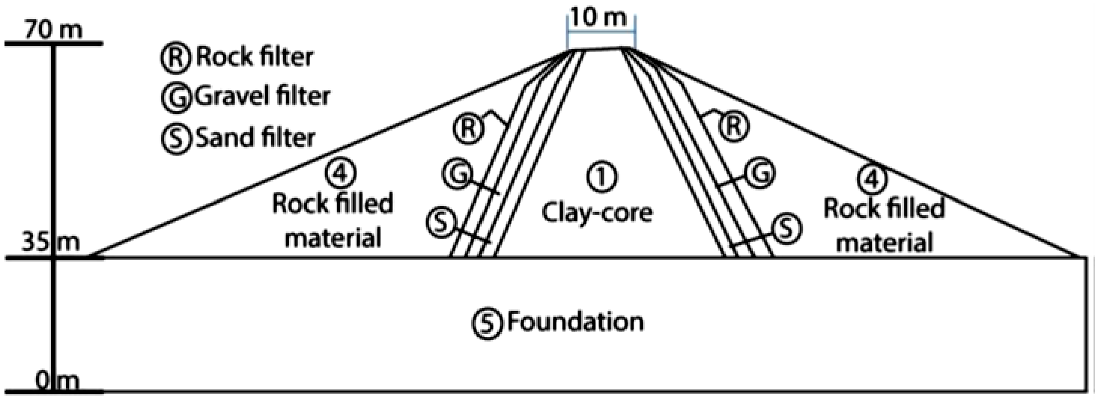

Fig 1. Cross section of clay-core rock fill dam (redrawn from Sunbul et al., 2017).

The selected material parameters for the dam are given in Table 1. In the analyses, we use two different soil structure models; these are Hardening soil and Mohr Coulomb models given in Table 1.

Table 1. Foundation and soil properties used in the geotechnical analyses.

Material	**Cohesion c**	**Friction Angle ϕ**	**Unit Weight ρ**	**Model**	**E_{50}^{ref}**	**E_{oed}^{ref}**	**E_{ur}^{ref}**
	kN/m²	**(˚)**	**kN/m³**		**kN/m²**	**kN/m²**	**kN/m²**
Clay Core	50	26	15.59	Hardening Soil	21000	21000	63000
Gravel Filter	0	34	21.09	Hardening Soil	32000	32000	96000
Rock Fill	0	37	19.52	Hardening Soil	45000	45000	135000
Rock Pieces Filter	0	42	21.18	Hardening Soil	34000	34000	102000
Sand Filter	0	32	20.99	Hardening Soil	29000	29000	87000
Foundation	1	42	22.07	Mohr-Coulomb	10^6	-	-

The dam with its foundation (down to 35 m) was modelled by generating triangular elements using 15node models. Assuming the height of dam as h; we extend the reservoir length up to 2h which is consistent to acquire more realistic results in the seismic response of a dam (e.g. Bayraktar et al., 2012; Kartal et al., 2017). The dam's clay core is modelled with the slope inclination of 1:2.5 upstream and 1:2.0 downstream. Filter material in both sides of the dam is consisted of rock, gravel and sand, with a slope inclination of 1:0.5 (Fig. 2).

Dams ought to be designed in considering an extreme earthquake with maximum intensity values. In view of this, we have investigated seismic behaviour of the CCR dam which was subjected to the M_d 7.1 earthquake and this is consistent with the idea of an extreme earthquake of about maximum intensity in structural seismic response analysis. That earthquake had a 0.4 g peak ground acceleration (PGA) value (Jarpe, 1989; PEER, 2018). The earthquake accelogram is presented in Figs 6 and 7 with the dynamic analyses. The earthquake duration time is 10 secs. and sampling interval is chosen as 0.01 secs.

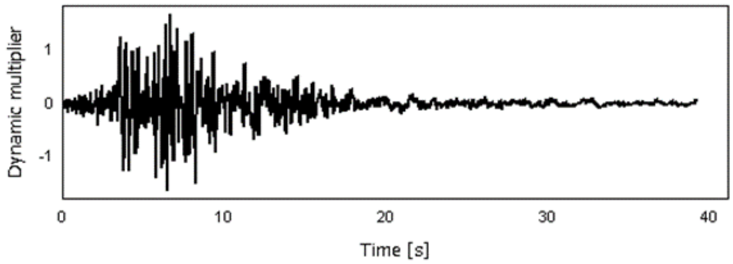

Figure 2. Strong ground motion data used in the dynamic analysis.

Three observation points (three element integration points: A, B and C), for which the time history graphs of the response quantities are plotted, are marked on the mesh as shown in Fig. 4.

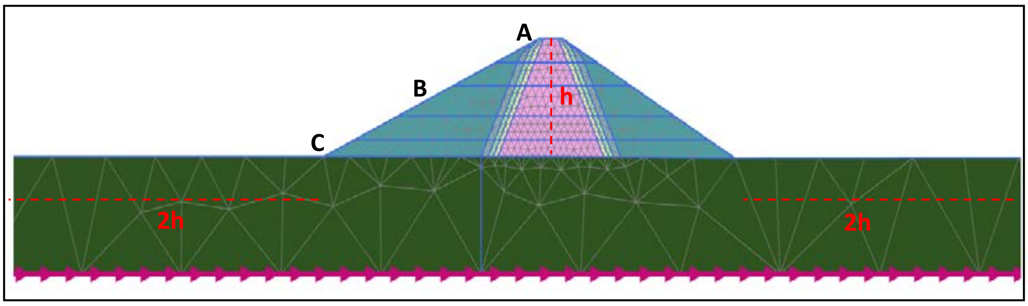

Figure 2. The dam is assumed as having symmetric zone sections (dam height:h, downstream length:2h, upstream length:2h) with the clay core and foundation (See also Table 1 for material properties used in the analysis).

RESULTS

Analyses were conducted in three steps in order to assess the displacements. These steps include static or dynamic analyses of displacements during; a) dam's construction phase, b) empty and full water reservoir phase and c) dynamic analysis under real earthquake data.

Construction Phase

Static solutions of the dam empty-reservoir system due to its gravity load are shown in Fig. 3. During stage construction, it is estimated a 30 day-period for the first 5 m-embankment. At each subsequent consolidation stages, we neglect the preceeding settlement values during the analyses.We also neglect the first stage consolidation as it was a natural settlement due to the initial excavations in the field. During the on-going calculations, we have obtained 2.9 cm, 8.8 cm, 16.11 cm and 23.48 cm, 28.16 cm over the staged consructions, respectively. Following the completion of dam body construction, we have obtained 62.05 cm in total settlement (Fig. 3).

It was observed that vertical displacement values at the points near the clay core were higher than those at the other points, whereas the vertical displacements were decreased inversely proportional to the outer layers from the clay core.

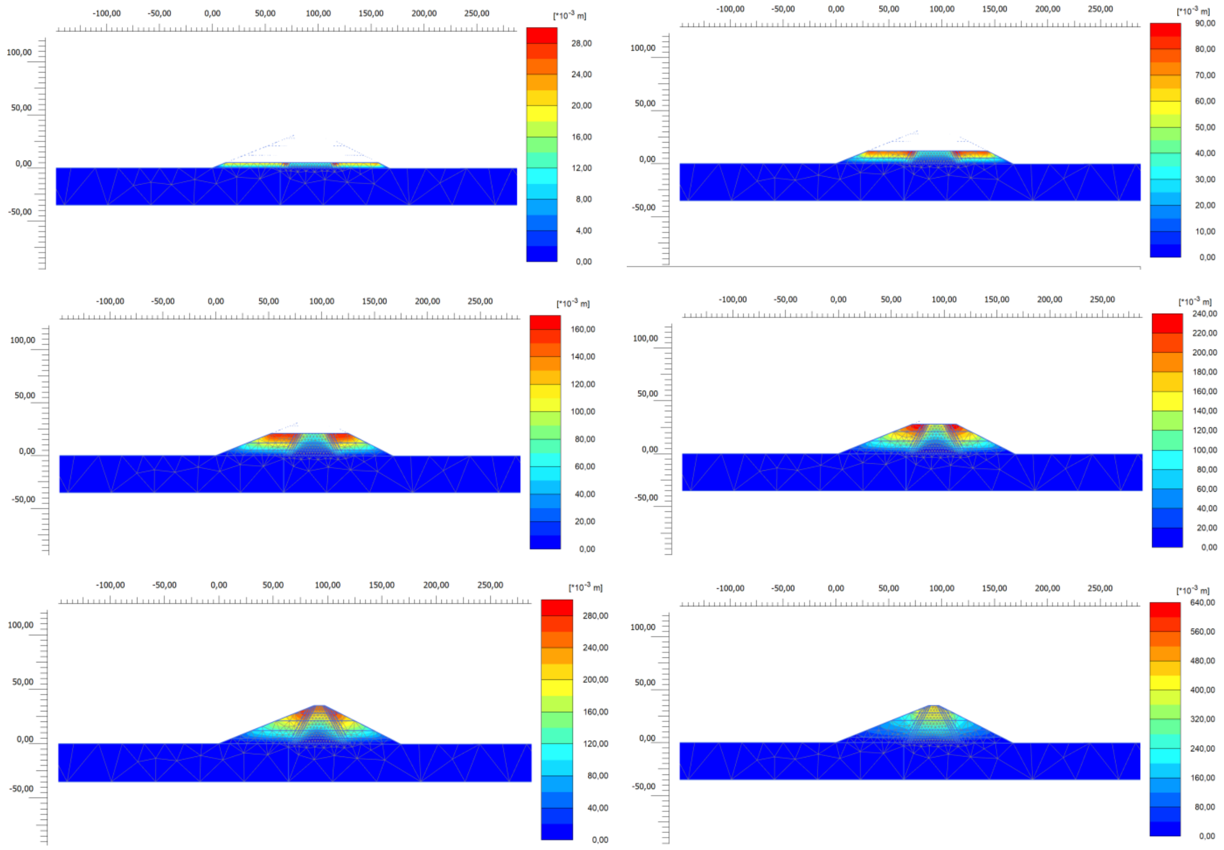

Figure 3. Stage construction steps in the static analysis.

Impounding Phase

The static analyses were also carried out for impounding phase. The reservoir water with an elevation of 32 meters was included in the model using applied pressures to the surface of the bottom and urface of the dam. During impounding, the hydrostatic force increases on the surface of the dam body. It is assumed that the hydrostatic force is zero at the top of the dam body. Here, we evaluate the hydrostatic pressure effect by changing the water level in the reservoir in the simulations. In full reservoir state, we obtained a settlement value of 47.36 cm while that value was 45.67 cm in the 15% water-reservoir state (Figs 4 and 5).

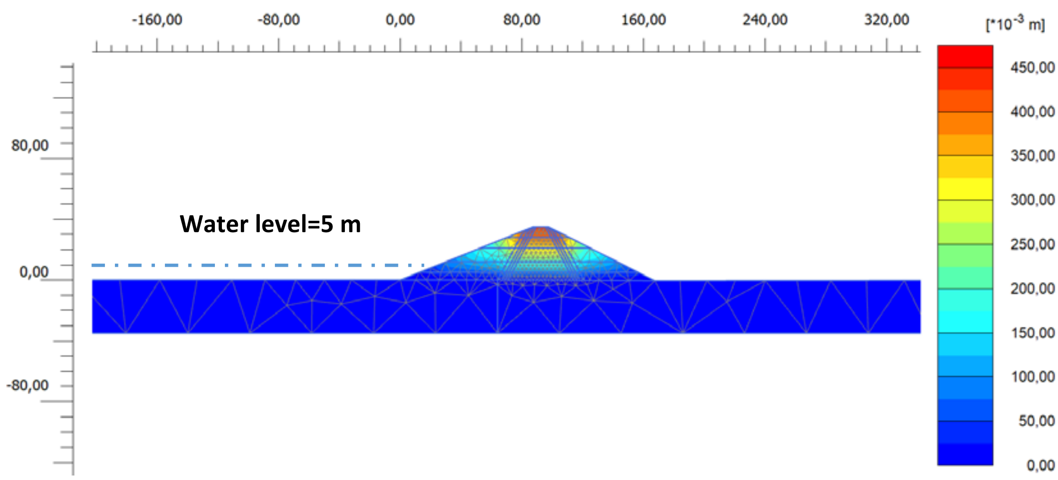

Figure 4. 15% water state, during impounding.

According to the predicted data, the largest displacement occurred in the clay core, which is the weakest material of the dam body. Moreover, when the empty state and the full water state of the dam are compared, it has been observed that the vertical displacement values, occurs at the crest, increase due to the water level rise. After starting the impounding stage, it was observed that the vertical displacements were visibly increased due to the hydrostatic pressure acting on the points B and C. The influence of the water level rise is also investigated at various points in the dam. In both cases (15% and 100% water reservoir states), we obtain higher displacement variations at A when compared to B and C. The results are in good agreement with previous studies (i.e. Parish, 2007).

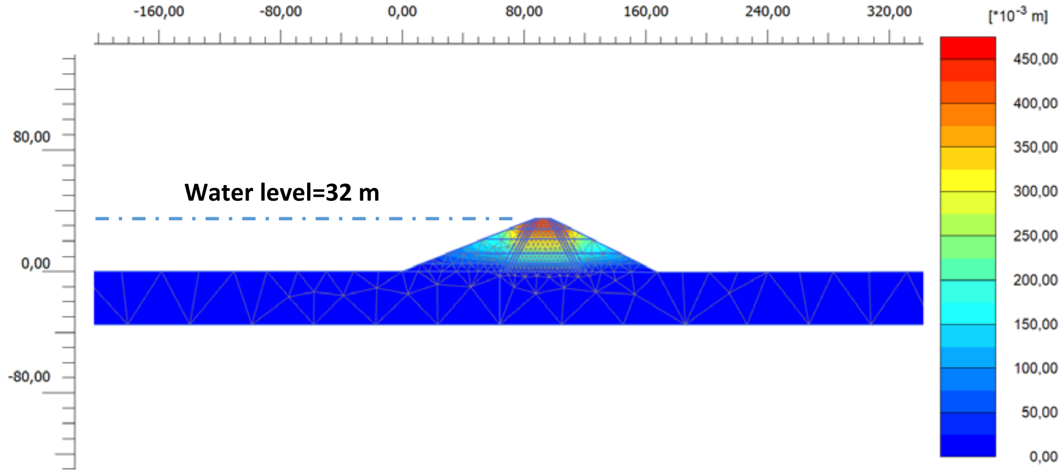

Figure 5. Full reservoir state during impounding.

Dynamic Phase

Fig. 6 shows the empty reservoir-vertical displacement time history of the dam under seismic loading for 10 seconds. The predicted maximum settlement occurs at dam body with a magnitude of 96.31 cm. The peak values are observed, under the strong ground motion record, over the slope faces.

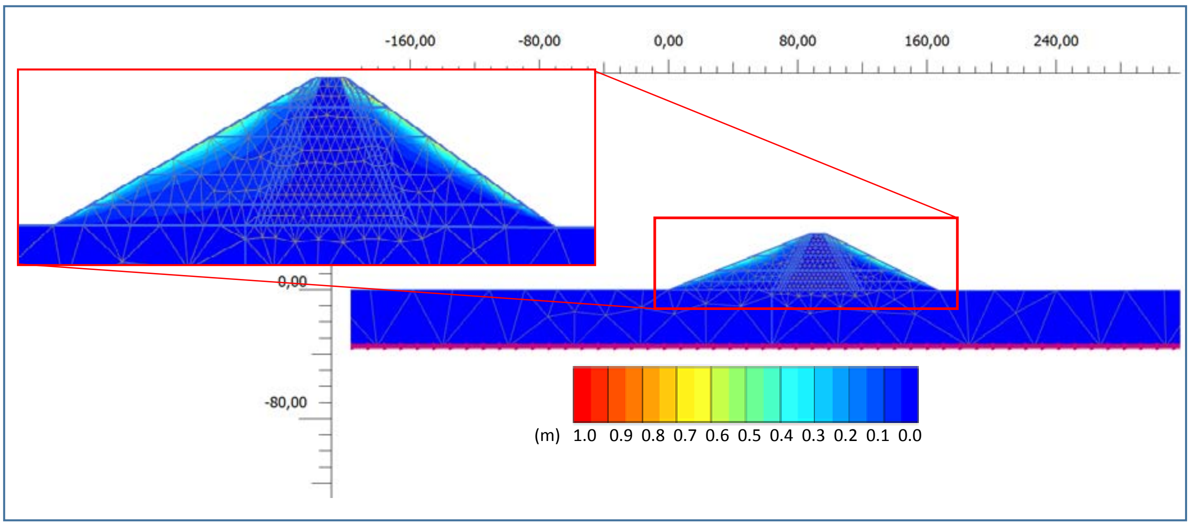

Figure 6. Empty reservoir state in dynamic analysis.

Fig. 7 shows the full reservoir-dynamic response of the dam under earthquake loading. The predicted maximum settlement occurs at upstream with a magnitude of 193.2 cm.

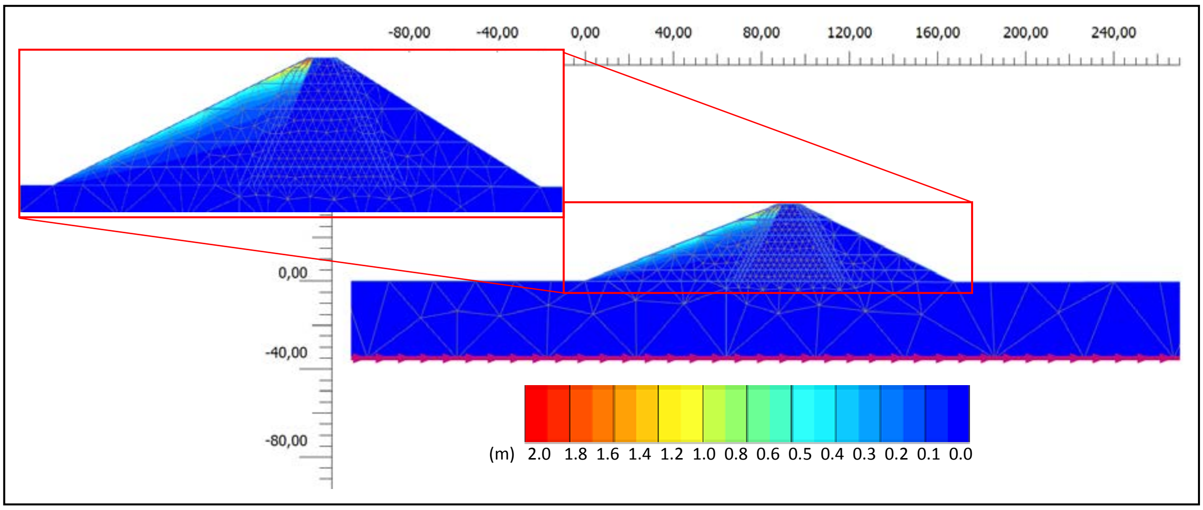

Figure 7. Full reservoir state in dynamic analysis

Fig. 8 shows the dynamic response of the dam under earthquake loading at the observation points of P_A, P_B and P_C. from Fig 8. We have observed maximum displacements at middle of the slope. There is no major change in displacements observed at P_A and P_C whereas increase in the displacements at P_B is obvious.

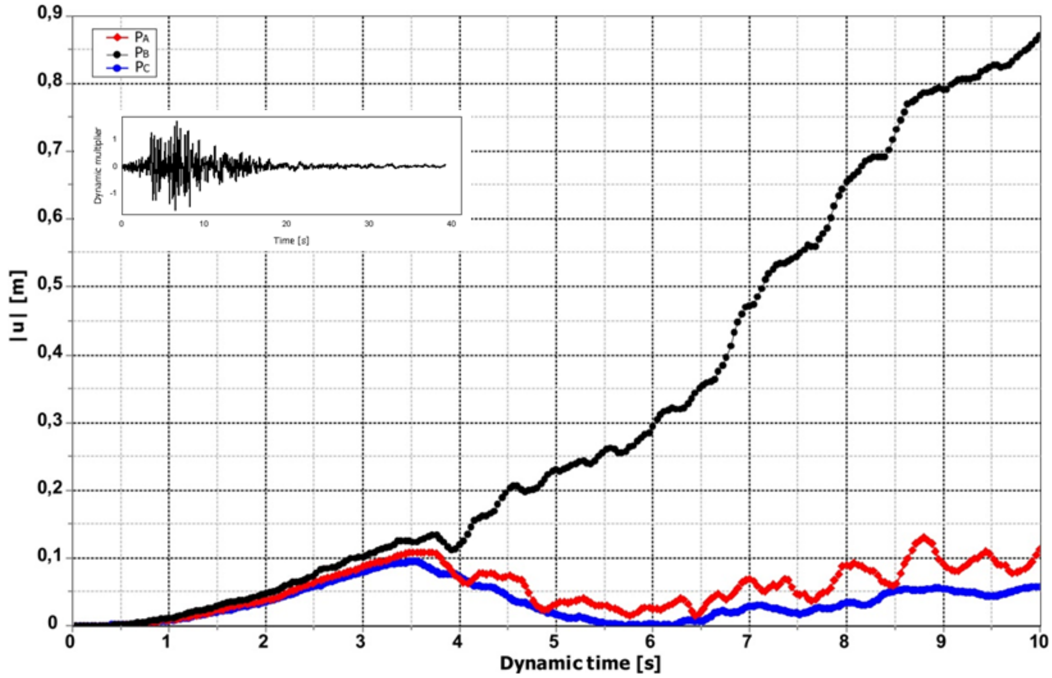

Figure 8. Dynamic analysis at P_A, P_B and P_C.

CONCLUSIONS

Performed numerical analysis justified with geotechnical data, has given nearly exact results of stress and displacements in body of dam. Basically the hardening-soil model due to including more soil parameters, can analyze these materials better than the other models. Studying the effects of earthquake is one of the important subjects in investigation of dam's stability. Here we analyse the static and dynamic response of a clay core in a systematic way. In the first phase, we create the dam model by stage construction approach, then the impounding phase is started. We also analyse the dynamic response of the dam under real earthquake data. In order to assess static and dynamic vertical displacements on the CCR dam; static and dynamic degrading behavior of a dam evaluated by using the finite element method. The results of this study are summarized as follows;

- During the construction phase (static state); the maximum displacements were observed at the crest of the dam. Following the completion of dam body construction, we have obtained 62.05 cm in total settlement

- During the impounding phase (static state); In full reservoir state, we obtained a settlement value of 47.36 cm while that value was 45.67 cm in the 15% water-reservoir state. The static state analyses show a gradual increase in the magnitude of vertical displacements during the impounding stage where the hydrostatic force acts on the surface of the dam body and causes additional force on the clay core section.

- During the dynamic phase; the CCR dam was subjected to the ground acceleration histories obtained by the 0.4 g peak acceleration value earthquake. The seismic excitation increased the magnitude of displacements when compared to the static phases. We observe 86 cm vertical displacement value at the middle of the dam during the first 10 sec of recording.

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