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THREE DIMENSIONAL ANALYSIS OF SEEPAGE IN 15-KHORDAD DAM AFTER IMPOUNDMENT*

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Abstract– In this paper, pore water pressure in the 15-Khordad dam, an earth fill dam constructed in a V-shaped valley with a clayey core and a height of 96 m was investigated following it's construction. Many vibrating-wire and standpipe piezometers were installed in the body of the dam. Pore water pressure monitoring was made from one week to ten months following the impoundment. The core was modeled by a finite element mesh, and 3-D transient and steady state analyses of pore pressures were performed and the results were compared with the monitored data. The trend in the monitored pore pressure was well modeled by the transient analysis. It was concluded that pore pressures in the cores of embankment dams may not achieve steady state conditions in some months, following the dam construction and impoundment. It was also observed that the selection of conductivity as a function of suction did not affect the results of modeling.

Keywords – Embankment dam, pore pressure, modeling, impoundment, transient analysis

1. INTRODUCTION

A two dimensional seepage analysis in a typical cross section of an embankment dam may replace its three dimensional analysis for simplicity. However, this simplification could be misleading in a V-shaped valley, where the dam cross section varies rapidly across the valley. The same problem exists if material property used in the dam and/or valley has high variations. In such cases, due to the implications of the flow, two dimensional seepage analyses should not be employed, or else very high safety factors have to be adopted, which could make the design uneconomical [1].

Many incidents are reported in the literature that manifest the inadequacy of applying a 2-D seepage analysis. As an example, in 1971, construction of an earth dam commenced in Mozambique where the right bank of the dam had a uniform 3-km-long cross section. Following the first impoundment, problems such as the formation of lagoons, saturated spots, and very high differences between predicted and measured amounts of seeping water and pore water pressures in the foundation of the dam were noted. A three dimensional seepage analysis made the causes of those problems clear. It was due to heterogeneity in the materials of the dam foundation which were not accounted for in the applied 2-D analysis [2].

Monitoring pore water pressure within earth and rock fill dams has been practiced extensively with safety probably being the first and the most important reason for it [3-5]. A secondary reason of less immediate concern to the owner, but of potentially great long range significance to the engineering profession is the need for better understanding of basic design concepts and of the 3-D seepage, deformation, and strength in soils and rock fills. Piezometers are the most common devices utilized for this purpose. Readings of a piezometer may also be used for monitoring the seepage, examining the effectiveness of the drains and cutoffs, and analyzing pore water pressure in dams during construction, impoundment, and rapid draw downs. One may categorize the applications of piezometers into two general categories; monitoring the 3-D water flow pattern, and providing an index for soil strength [6-8].

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Various types of piezometers are usually installed in an embankment dam so that they compensate one another's disadvantages [6]. Among widely used types are open standpipe and vibrating wire piezometers. While open standpipe piezometers are simple durable devices with relatively high reliabilities, they need to transmit a "large" amount of water before they can reflect a certain change in pore water pressure. On the other hand, vibrating wire piezometers are hydro electrical devices, which operate based on a vibrating wire transducer with no need for transmitting water. However, during the dam construction, filling and compaction of earth material may expose the transducer cell to an enormous increase in the total stress. If the cell is not rigid enough, then its deformations will change the wire tension, in which case, the piezometer readings would not be reliable [6, 8].

Piezometer readings are usually utilized to model and analyze the behavior of pore water pressure in an embankment dam [7]. Pore water pressures may be modeled under a steady state or transient condition, depending on the situation. For example, if the reservoir level remains constant for a "long" period of time, one may assume a steady state for pore water pressure. On the other hand, in order to model pore pressures following dam impoundments, it seems necessary to perform a transient analysis. In any case, whether the pore pressure has reached a steady state or not is not always a simple question to answer. Monitoring and modeling pore pressures in dams are common approaches taken to answer such questions [7].

Although applying a correct set of boundary conditions is vital in obtaining reliable results from seepage analyses in heterogeneous embankment dams, such boundary conditions are usually applied using certain simplifications [9]. Simplifications of boundary conditions are applied in different ways at the upstream shell, the core, the filters, and the downstream shell. A simple, but a common approach in the finite element or finite difference seepage analysis is to eliminate the shells and the filters because of their high permeabilities. In this approach, only the core is modeled and the reservoir elevations along with the known downstream pore pressures are applied as the upstream and downstream boundary conditions, respectively.

In this study, monitored pore pressure heads during the first ten months following the construction and impoundment of the 15-Khordad dam, a heterogeneous earth fill dam constructed in a V-shaped valley in Iran, are investigated. The core is modeled by a finite element mesh, appropriate boundary and initial conditions are applied, and 3-D steady state and transient seepage analyses are performed. Modeling results are compared with the monitored heads, and the response of pore water pressure in the core to the dam impoundment is discussed. The effects of different input parameters such as permeabilities are also considered.

2. THEORY

There are two approaches in water flow analysis through porous media. The more common one is saturated flow analysis in which water is assumed to flow only in the saturated part of the domain. In this approach, the location of the phreatic surface should be determined by means of some iterative methods such as Variable Mesh, Adaptive Mesh, and Fixed Mesh methods. Because of some restrictions, these methods are not applicable to three dimensional problems [10]. The second approach is saturated/unsaturated flow analysis in which water may flow through both saturated and unsaturated regions. Steady state seepage through an unsaturated soil is mathematically characterized by the Laplace equation, which would become nonlinear if there are variations in the soil properties. It is known that hydraulic conductivity, as an important soil property, is not a constant in unsaturated soils but varies with the volumetric water content and/or pressure [9-11].

In order to model unsaturated flow through porous media, a complete function of conductivity versus pressure should be specified for the material. Adopting a constant hydraulic conductivity function for an unsaturated soil may lead to unrealistic results such as an impractical position for the phreatic surface or too high proportions of flow through the unsaturated zone. Even if the conductivity function is an estimate, the results will be more realistic when a complete function is used rather than a constant value for conductivity [9]. The level of accuracy required to define the hydraulic conductivity of the material may be evaluated by performing several analyses with different assumed functions. Performing such a sensitivity analysis can greatly increase the confidence level of the computed results.

From a theoretical viewpoint, fundamental equations of unsaturated flow may be applicable to three dimensional problems given that the soil hydraulic conductivity function is determined in 3-D. Usually, the conductivity function is determined by means of experimental tests. There are also some empirical equations proposed for calculating the conductivity function of a soil from its Soil Water Characteristic Curve (SWCC) [9, 10]. In any case, the governing differential equation used in the formulation of the seepage analysis is

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y \frac{\partial H}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z \frac{\partial H}{\partial z}\right)+Q=\frac{\partial \theta}{\partial t} \tag{1}$$

where H is the hydraulic head [L], Kx, Ky, and Kz are hydraulic conductivities [L/T] in x- y-, and z-directions, respectively, Θ is the volumetric water content [L^3L^{-3}], Q is flux per unit volume [LT^{-1}] added to or withdrawn from the control volume, and t is the time [T]. This equation, the equation of continuity in an anisotropic porous media, states that the difference between the flow (flux) entering and leaving an elemental volume at a point in time equals the rate of change of the volumetric water content. More fundamentally, it states that the sum of the rates of change of flows in x-, y- and z-directions plus the external applied flux is equal to the rate of change of the volumetric water content in the control volume (with respect to time).

Under steady-state conditions, the flux entering and leaving an elemental volume would be the same at all times. Consequently, the right hand side of the equation vanishes and the equation reduces to

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y \frac{\partial H}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z \frac{\partial H}{\partial z}\right)+Q=0 \tag{2}$$

The change in volumetric water content in Eq. (1) may be related to the change in pore water pressure by the equation

$$\partial\Theta = m_w \partial u \tag{3}$$

where m_w is the slope of SWCC at any suction [$M^{-1}LT^2$] and u is the pore water pressure [$ML^{-1}T^{-2}$].

Using Eq. (3), volumetric water content may be eliminated from Eq. (1)

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y \frac{\partial H}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z \frac{\partial H}{\partial z}\right)+Q=m_w \gamma_w \frac{\partial (H-y)}{\partial t} \tag{4}$$

where y is the elevation head [L] and γ_w is the unit weight of water [$MT^{-2}L^{-2}$]. Equation (4) is the governing equation for 3-D transient seepage analysis of pore pressure in soils that was solved by the program under the appropriate initial and boundary conditions using a finite element method.

3. CHARACTERISTICS OF THE DAM

15-Khordad dam is constructed on the Qomrud River, located near the city of Qom, Iran. It is an earth fill dam with a central clayey core. With the excavated 30-m sedimentation layer at the riverbed, the dam has a maximum construction height of around 96 m. The crest is 320 m long and 10 m wide with an elevation of 1448.8 m from the mean sea level. The core has a slope of 1H:5V with maximum and minimum widths of 37.5 m and 5 m, respectively. The dam is constructed in a V-shaped valley with an aspect ratio of ~ 3.3 (Fig. 1). All elevations on Fig. 1, and also in the rest of the article, are given in meters from the mean sea level.

Various types of instruments such as electrical piezometers, electrical pressure cells, standpipe piezometers, inclinometers, settlement gauges, and accelerometers were installed throughout the dam. These instruments were installed at different elevations in 5 monitoring sections (Fig. 1). Piezometers at section 3-3, the highest monitoring section of the dam, are shown on Fig. 2. As shown on the figure, six electrical piezometers were installed on the concrete slab of the foundation (EP1~EP6), 16 vibrating wire piezometers were installed at elevations of 1378, 1392, 1410, and 1430 m (EP7~EP22), and four standpipe piezometers were installed at elevations of 1357.5 and 1392 m (SP1~SP4). Heads monitored by electrical and standpipe piezometers at section 3-3 at different elevations were investigated in this study.

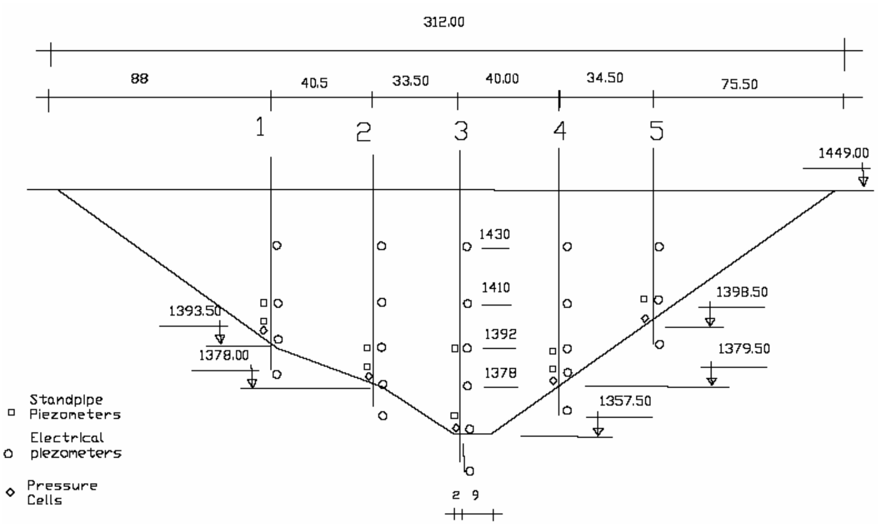

Fig. 1. Details of monitoring sections at the cross section of the dam valley

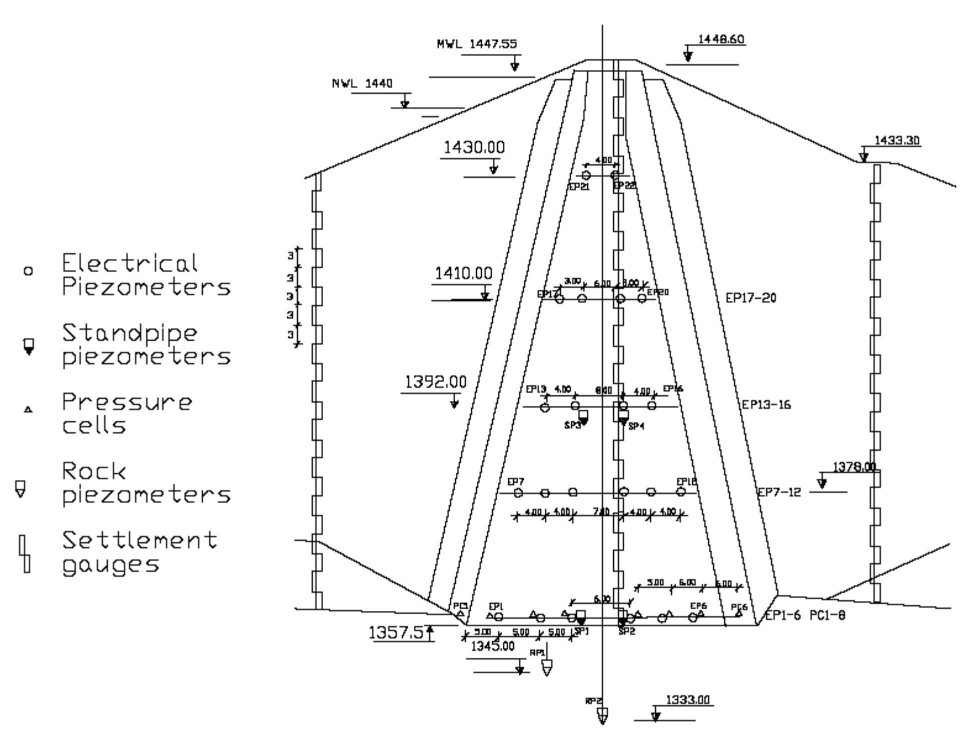

Fig. 2. Details of instrumentation at the monitoring section 3-3

4. MODELING

The dam hydraulic behavior was modeled by Seep3D software provided by Geo-Slope. This software uses a finite element method for analyzing unsaturated and saturated flow through porous media under steady and transient conditions. Three dimensional seepage analyses were performed covering a span of ten months after the start of the dam impoundment. Pore water pressures at section 3-3 at different times along this period were evaluated.

A finite element mesh of the clayey core used for the analyses of this study is shown on Fig. 3. It was known that modeling porous media which contain materials with widely contrasting hydraulic conductivities might cause numerical convergence difficulties [10]. Since the shells of the dam were considerably more conductive than the core, zero head dissipation was considered through the shells, and therefore, heads at all nodes along the upstream face of the core were set equal to the reservoir level. Consequently, there was no need to include the upstream shell in the analyses.

The downstream shell was excluded from the model. The rationale was the fact that materials such as rockfill shells have essentially a very steep (almost vertical) conductivity versus pressure function. In other words, portions of such material that are below the water table have a relatively high hydraulic conductivity, while portions above the water table have an infinitely low hydraulic conductivity. The water table usually drops considerably through the core of an earthfill dam, and therefore the downstream shell will remain above the water table and unsaturated [12]. Due to very low hydraulic conductivity of the downstream shell and negligible flow through it, this shell was excluded from the model.

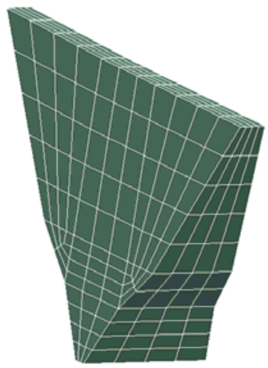

Fig. 3. Finite element mesh for the clayey core of 15-Khordad dam

The average monitored head elevation at the end of the dam construction (el. 1410) was applied in the model as the initial condition for all nodes. Monitored reservoir levels were applied as a time-dependant head boundary condition at the upstream face of the core, while the downstream face of the core was left as a potential seepage boundary.

5. RESULTS AND DISCUSSIONS

Results of this study are presented in two sections. First, pore pressures monitored by piezometers installed at different elevations in the core are presented and discussed. Second, the results of modeling pore pressures under steady state and transient conditions are described and compared with certain monitored data.

a) Monitored pore pressures

Construction of the dam started in March, 1994 and lasted for ~12 months. Following construction of the dam body, impoundment of the reservoir and monitoring pore pressure heads in the core started. In this part of the article, monitored heads in section 3-3 (Fig. 2), collected during the period of the first ten months following the dam construction and impoundment, are presented and discussed.

I. Piezometers installed at el. 1357.5 (the foundation level): A total of 6 vibrating wire (EP1~EP6) and two standpipe piezometers (SP1~SP2) were installed at this elevation. They were numbered sequentially from the upstream to the downstream face of the core (Fig. 2). EP1, EP5, and SP2 were apparently destroyed during the construction because no data was available for these piezometers. Figure 4 shows the readings of available piezometers as well as the reservoir level. As shown on the figure, the reservoir level remained almost constant for a period of 7 months (el. 1408) between early and late dam impoundments. In this period, some piezometers showed heads higher than the reservoir level. It is postulated that a high pore pressure induced by construction existed in the core, which was dissipating gradually. Head dissipation was slow, especially near the upstream face of the core (EP2, EP3, and EP4), due to the low hydraulic gradient and conductivity there. A faster dissipation, observed in piezometer EP6 (from el. 1410 to el. 1402) in the same period, was attributed to its location being close to the highly conductive downstream filter and high gradient there.

During the late impoundment of the dam a “rapid” increase in the reservoir level (from el. 1408 to el. 1429.1) occurred in a two month period. In response to this impoundment, piezometers near the upstream face of the core responded faster compared to the downstream face, so that EP2, EP3, EP4, and EP6 showed increases of 12, 7.4, 6.2, and 2.8 meters in their water levels, respectively. This behavior was expected due to the shorter distance between the piezometers near the upstream face and the reservoir.

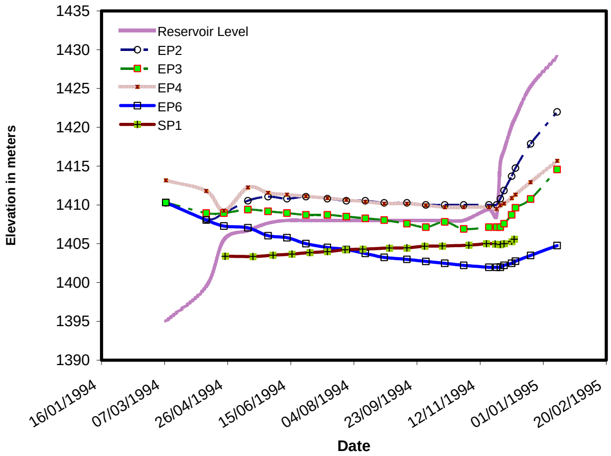

Fig. 4. Monitored heads in piezometers installed at elevation 1357.5

II. Piezometers installed at el. 1378: Monitored heads at six piezometers installed at this elevation (EP7~EP12) are shown on Figure 5. As in the previous elevation, the general trend during the constant reservoir level is that piezometers show higher heads near the upstream and lower ones near the downstream face of the core. Piezometers near the upstream face of the core (EP7, EP8, and EP9) also show heads higher than the reservoir level and demonstrate slow or no dissipation. During the same period, EP11 and EP12, which are close to the downstream filter, show a fast reduction in their water levels. It is postulated that the high pore pressures induced by construction hardly dissipated near the upstream face of the core (EP7, EP8, EP9, and EP10) due to the low gradient and conductivity, while they dissipated much faster near the downstream face (EP11 and EP12) due to the existence of a highly conductive filter and also the high gradient there.

EP7, which is close to the upstream face, responded almost simultaneously to the late impoundment of the reservoir. Moving downstream, EP8 to EP11 exhibited slower responses with fewer total increases in their water levels, respectively. In general, the behavior of the pore pressure at this elevation was similar to that explained at el. 1357.5.

III. Piezometers installed at el. 1392, el. 1410, and el. 1430: EP13 to EP16 were installed at elevation 1392 (Fig. 2). Figure 6 shows the monitored heads obtained from these piezometers. Their general behavior is similar to those installed at lower elevations except for the fact that at this elevation fewer piezometers (only EP13) show heads which are higher than the reservoir level. As discussed before, the high head at this piezometer was induced during the dam construction which dissipated gradually with time. The response of piezometers to the late impoundment of the dam was also similar to that at lower elevations.

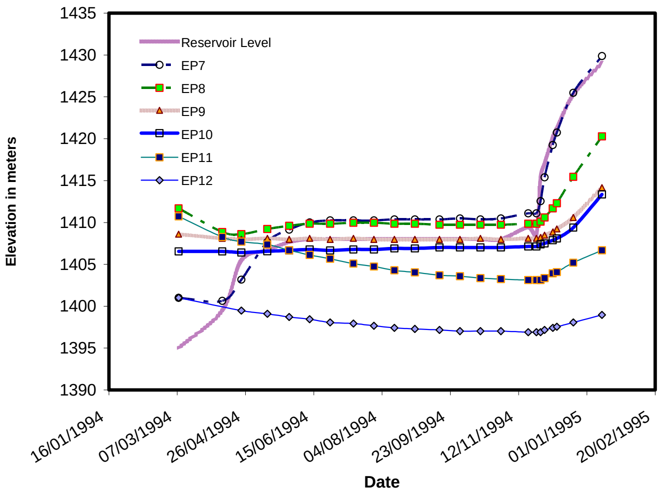

Fig. 5. Monitored heads in piezometers installed at elevation 1378

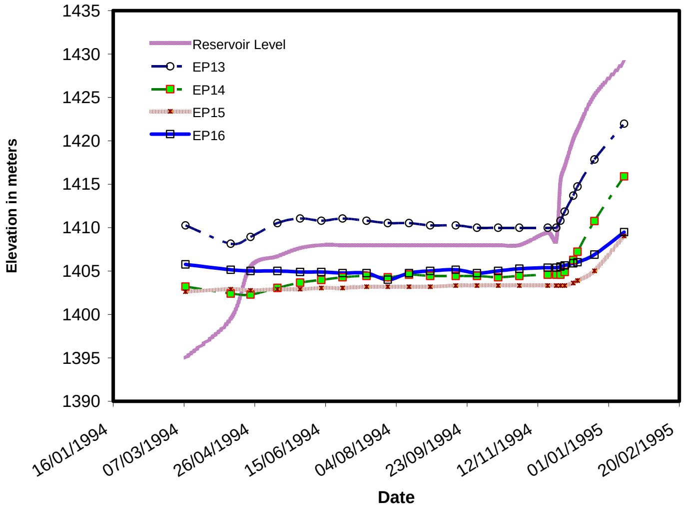

Fig. 6. Monitored heads in piezometers installed at elevation 1392

Figure 7 shows the heads monitored by four piezometers installed at el. 1410 (EP17 to EP20). The general trend in heads during the constant reservoir level is similar to those at lower elevations. Just before the late dam impoundment, however, some of the piezometers installed at this elevation showed zero or slightly negative pore pressures. This was attributed to the head induced by construction being at or slightly less than their elevations. During the late impoundment of the dam, when the reservoir level rapidly increased to 1429.1, pore pressure in these piezometers increased subsequently.

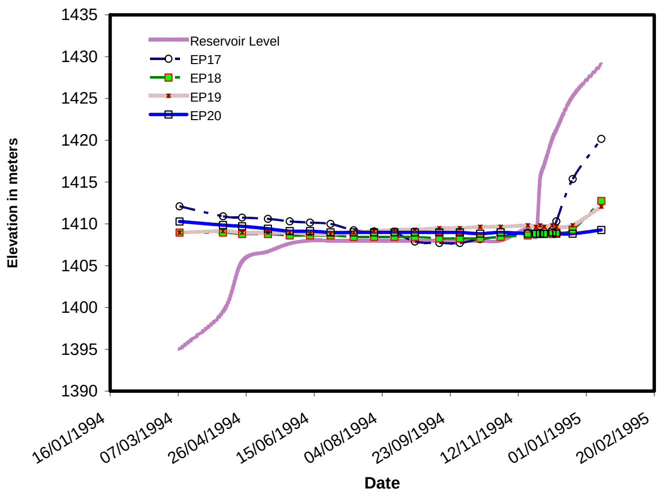

Fig. 7. Monitored heads in piezometers installed at elevation 1410

During the entire period of the study, piezometers installed at el. 1430 showed negative pore water pressures which were not considered in this paper. This was attributed to the reservoir level always remaining lower than this elevation during the study.

b) Modeling results

The value of hydraulic conductivity as a function of pressure was not available for the core material. Therefore, having the conductivity of the material at full saturation (10^{-10} m/s), two distinct but typical functions (shown on Figs. 8a and 8b) were fitted to it. Sensitivity analyses were performed and pore pressure heads in the core were calculated using both functions. As an example, the variations of head vs. time in EP13, obtained by application of these two functions, are presented on Fig. 9. As can be seen on the figure, the results obtained from both functions coincide. Such coincidence was also seen in other points of the core, hence it was concluded that the results of the study were not affected by the conductivity function. It is postulated that overall seepage was dominated by hydraulic characteristics of the saturated zone with little (or no) effect from the HC-S (Hydraulic Conductivity-Suction) curve.

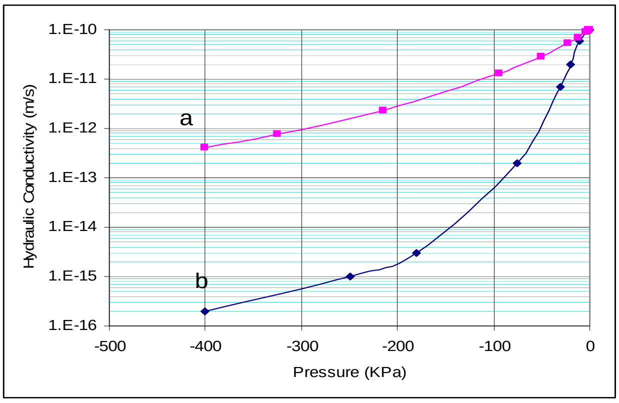

Fig. 8. Typical conductivity versus pressure functions used for unsaturated analyses of the core

As a typical example, calculated heads in one piezometer (EP7) and reservoir level as functions of time are shown on Fig. 10. As shown on the figure, the general trend in both are very similar except for the fact that as the reservoir level increased rapidly at early and late impoundments, the calculated head responded with a slower rate of increase. The same behavior was observed in all data points. However, for brevity, in the rest of the article, calculated and monitored heads at different elevations across the core are compared only at two interesting times. These times are shown on Fig. 10 as two vertical lines. Instant 1 is the moment when the reservoir level had been approximately constant for 7 months, and just before the late reservoir impoundment started. Instant 2 is almost two months later than instant 1 and is the time when the impoundment of the dam was complete. One may expect the pore water pressure across the core to be at steady state at instant 1 and at transient at instant 2.

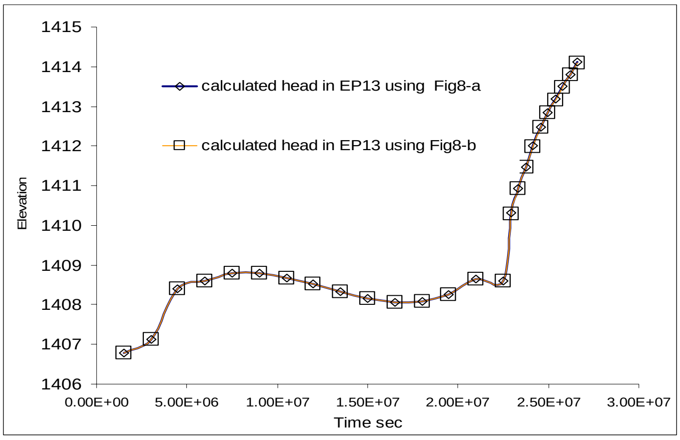

Fig. 9. Head versus time at EP13 obtained by application of two conductivity functions

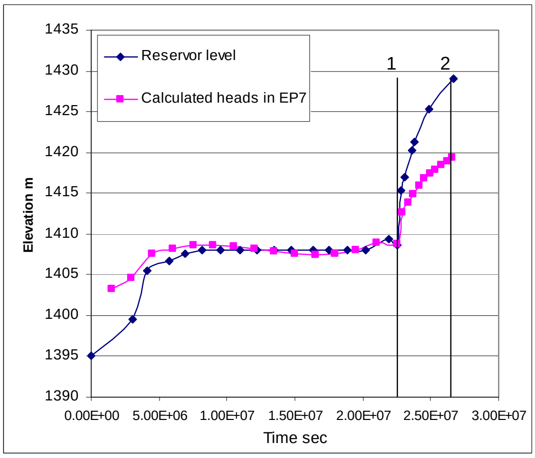

Fig. 10. Calculated heads in EP7 and reservoir level as functions of time

Monitored heads at el.1357.5 at instant 1, as well as calculated heads from the steady state and transient analyses at the same point and time are shown on Fig. 11. At this time the reservoir level was at el. 1408, while the average monitored head induced by construction (the initial condition) was 1410 (Fig. 4). As shown on Fig. 11, monitored heads were surprisingly close to the results of the transient analysis, reflecting that the pore pressures had not reached their steady state value in almost 7 months. As expected, at points located near the downstream face of the core, monitored heads and the results of transient analysis departed from the initial conditions much faster than the points near the upstream face. This was due to the corresponding boundary conditions imposed at downstream and upstream faces of the core.

Heads at el.1378 at instant 1 are shown on Fig. 12. The general trend in monitored heads is similar to the trend at el. 1357.5. However, at this elevation monitored data were better simulated by the transient analysis results. As before, monitored heads had moved considerably from their initial toward their steady state conditions at downstream locations, while heads at other parts of the core had not departed much from their initial conditions yet. In general, considering seven months at almost constant reservoir level after the early impoundment, to one's surprise, pore pressures were still at the transient state, especially at the interior parts of the core.

Heads at el. 1392 at instant 1 are shown on Fig. 13. At this elevation only four monitored heads were available at the core section (Fig. 2). As can be seen on the figure, the trend in monitored heads across the core is approaching the steady state. This is particularly true at locations near the upstream face of the core, as two monitored heads near the downstream face show, more or less a transient state for the pore pressures there.

Heads at el. 1410 at instant 1 are shown on Fig. 14. The initial heads in the core, induced by construction, were about 1410, meaning that the initial pore pressure at this elevation would be approximately zero. Since the reservoir level at instant 1 was below 1410 (about 1408), thus one would expect pore pressures to change from zero to negative values at this elevation. Both the monitored data and transient analysis results, shown on Fig. 14 confirm the occurrence of negative pore pressures (heads less than 1410). Indeed, four monitored heads at this elevation show a trend similar to the trend observed at el. 1392 (i.e., moved toward the steady state at the upstream part and close to the transient analysis results in downstream parts of the core). However, because the installed piezometers were incapable of measuring negative pressures, we do not draw any quantitative conclusion from this figure.

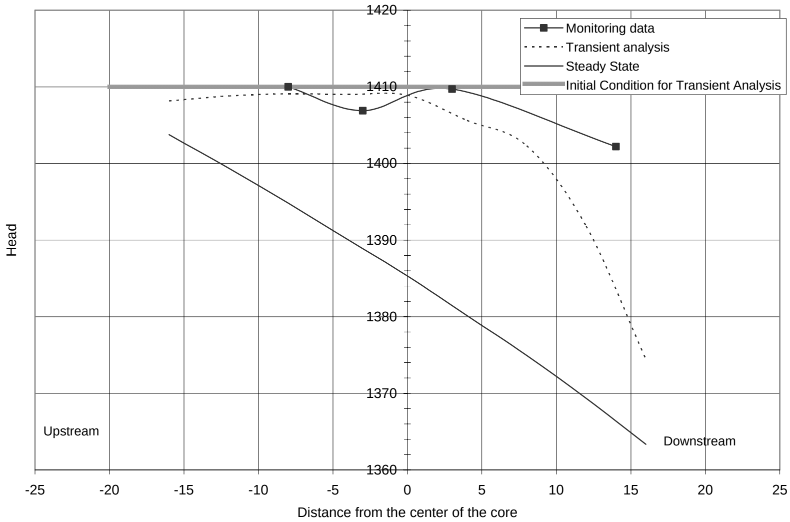

Fig. 11. Heads at instant 1 at elevation 1357.5 versus horizontal location

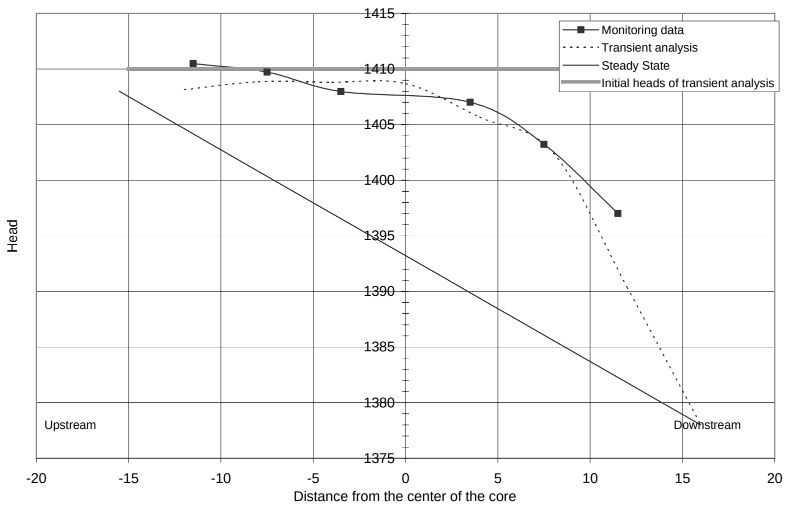

Fig. 12. Heads at instant 1 at elevation 1378 versus horizontal location with respect to the center line of the core

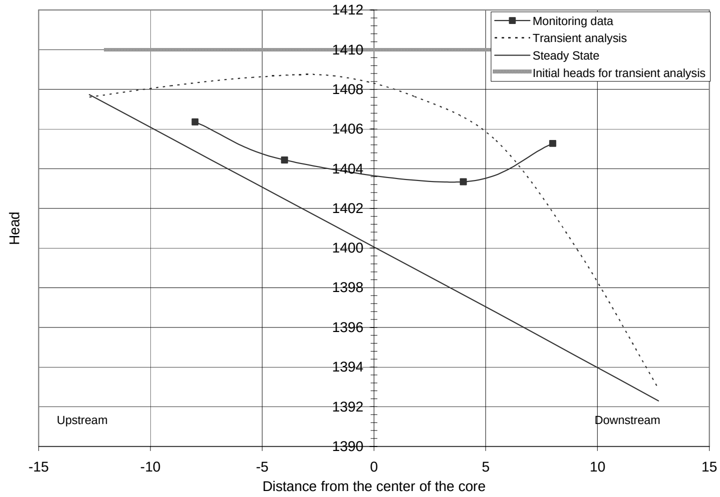

Fig. 13. Heads at instant 1 at elevation 1392 versus horizontal location with respect to the center line of the core

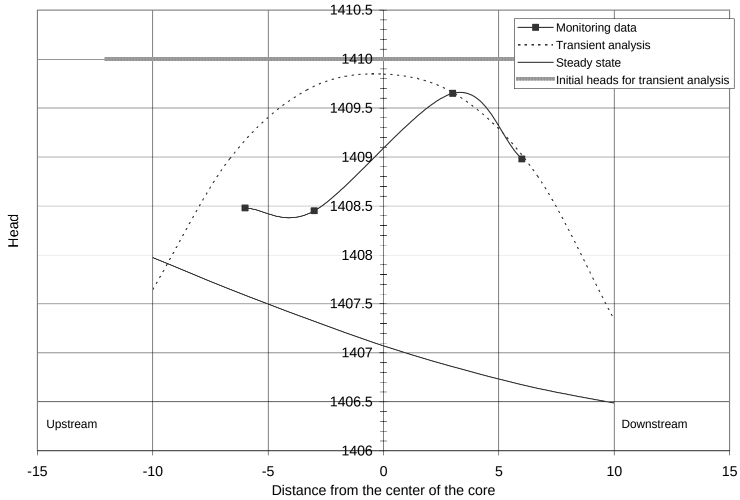

Fig. 14. Heads at instant 1 at elevation 1410 versus horizontal location with respect to the center line of the core

Figures 15 and 16 show monitored heads at instant 2 at elevations 1357.5 and 1378, respectively. The initial condition of a constant head induced by construction (el. 1410), the result of transient and steady state analyses are also shown on these figures. Applied upstream boundary condition at instant 2 was the reservoir level which reached el. 1429.1 in about two months. This elevation was greater than the initial heads, and therefore, one would expect the pore pressures in locations close to the upstream face of the core to increase from their initial value toward the steady state values. In fact, the increase in pore pressures in the core was observed as far as a few meters toward the downstream from the center line (Figs. 15 and 16). In locations close to the downstream face of the core, where pore pressures were expected to decrease from their initial toward their final (steady state) values, such a decrease was actually observed. However, dissipation of pore pressures there were less than what was predicted by the transient analysis. In general, the trend in observed heads is very similar to that in the result of the transient analysis, only with an upward shift.

The heads at el.1392 at instant 2 are shown on Fig. 17. Considering initial and steady state heads on this figure, one would expect pore pressures to increase on the upstream half of the core and decrease on the downstream half. Such a change (trend) in heads was actually observed. However, dissipation of pore pressures in the downstream half of the core was less than what was predicted by the transient analysis.

Similar to the case in previous elevations, the trend in monitored heads was comparable to that in the results of the transient analysis with an upward shift.

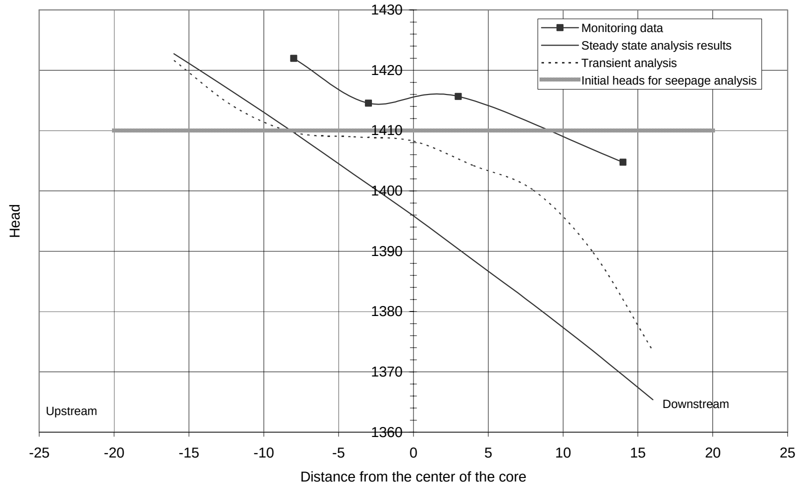

Fig. 15. Heads at instant 2 at elevation 1357.5 versus horizontal locations with respect to the center line of the core

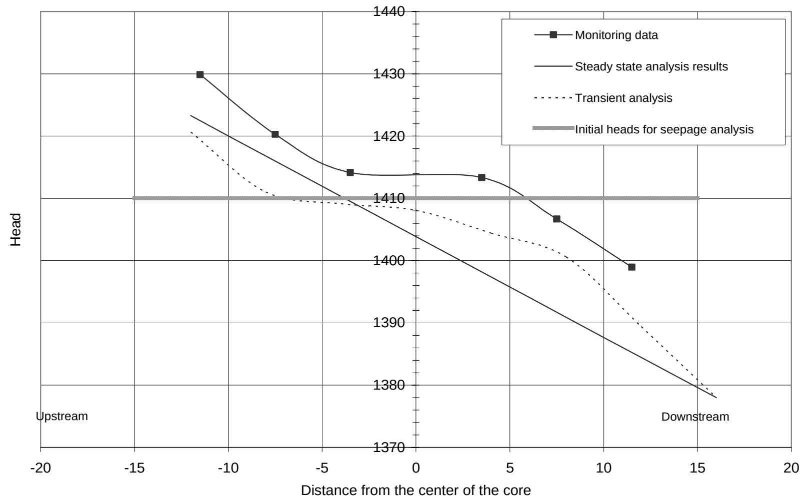

Fig. 16. Heads at instant 2 at elevation 1378 versus horizontal locations with respect to the center line of the core

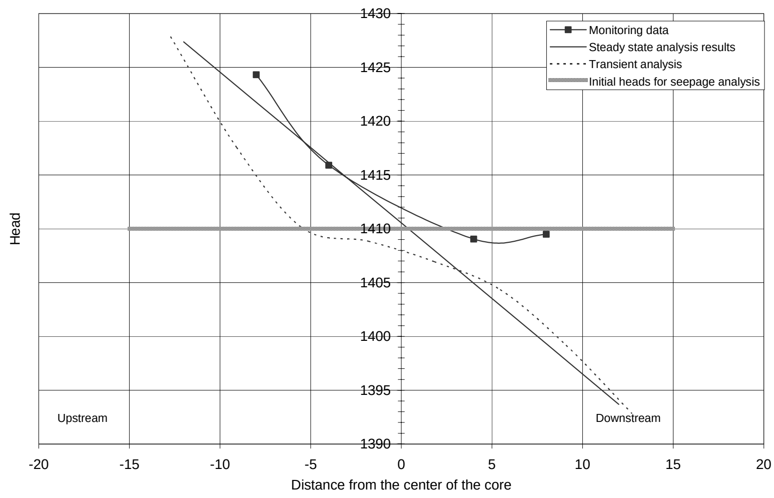

Fig. 17. Heads at instant 2 at elevation 1392 versus horizontal locations with respect to the center line of the core

Heads at el.1410 are shown on Fig. 18. As shown on the figure, the steady state heads are entirely greater than the initial head (el. 1410), thus one would expect all pore pressures in the core to increase at this elevation. Monitored heads show this trend except for a slight decrease observed in a piezometer installed a few meters toward downstream from the center line of the core. As before, the trend in the observed heads was very similar to that in the result of transient analysis, only with a slight upward shift.

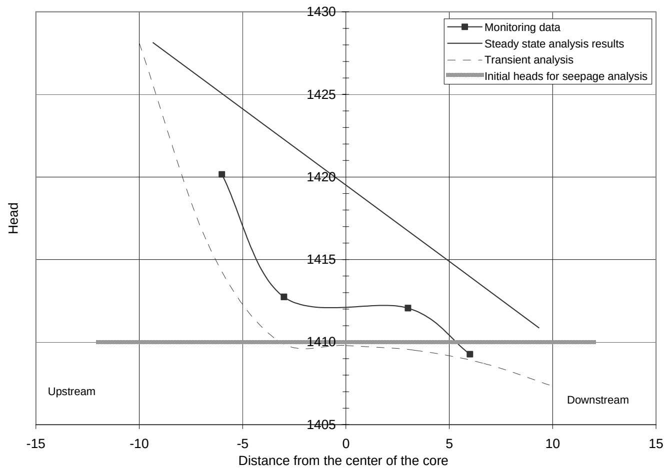

Fig. 18. Heads at instant 2 at elevation 1410 versus horizontal locations with respect to the center line of the core

6. CONCLUSIONS

Pore pressures in the clayey core of 15-Khordad dam, an earth fill dam constructed in a V-shaped valley in Iran, were analyzed while the dam experienced an early impoundment, a period of almost constant reservoir level, and a late impoundment. The core was modeled by a finite element mesh, 3-D transient and steady state analyses of pore pressures were performed, and results compared with the monitored data. Results showed that the dam construction caused pore pressure build up such that el.1410 was registered throughout the core by piezometers as the average induced head. During the seven month period of almost constant reservoir level (el. 1408), the excess pore pressures induced by construction were dissipating. To one's surprise, at the end of this period, pore pressures were still at the transient state, especially at the interior parts of the core. Before the pore pressure reached a steady state condition, the late impoundment of the dam (up to el. 1429.1) occurred. The trend in the pore pressure build up, due to this impoundment, was well modeled by the transient analysis. It was concluded that pore pressures in embankment dams may not achieve steady state conditions in the months following the dam construction and impoundment. It was also observed that the selection of conductivity as a function of suction did not affect the results of modeling.

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