Numerical Modeling of Pore Water Pressure Development in MOSUL Dam

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ABSTRACT

A finite element method is useful tools to be applicable in many geotechnical engineering topics. In this paper the pore water pressure development within the clay core of MOSUL earth dam were investigate considering the saturated/unsaturated conditions using GEO-SLOP software. Three selected sections through the dam were chosen for the analysis (in the middle, right, and left sides of the dam to cover the dam body). The investigation of the dam body response to the earthquakes with many values of the maximum horizontal acceleration was done. Normal, maximum, and minimum operation water levels with possibility of rapid drawdown of water level during (8,21,30) days were also consider. Transient and steady state analysis of pore water pressure was performed, finally the results were compared with the actual field data.

Results indicated that, the maximum pore water pressure was occurred for the nodes in the upstream near of the core base at the time during and after the end of earthquake shaking. The results of the study also presented a positive pore water pressure development in the lower part of the core when the water was at maximum, normal, and minimum operation levels, with negative values near the crest of the dam. high pore water pressure was record through sec6 and sec4, for the rapid drawdown of water level at time 8 days. Finally, nearly identical pore water pressure results are obtained from the numerical analysis and the recorded field piezometers readings data.

Keywords: Earthquake, MOSUL Dam, Pore water pressure, rapid drawdown, Unsaturated soil.

دراسة نظرية لضغط ماء المسام المتولد في لباب سد الموصل

الخلاصة

تعد طريقة العناصر المحددة من الطرق العملية القابلة للتطبيق في العديد من مواضيع هندسة الجيوتكنك. في هذا البحث تم دراسة حالات مختلفة لضغط ماء المسام المتولد في لباب سد الموصل الواقع شمال مدينة الموصل/ العراق. وبثلاث مقاطع مختلفة تم اختيارها في مواقع مختلفة لأجل تغطية جميع أجزاء جسم السد. تم دراسة ثلاث حالات لمستوى الخزن مع احتمالية حدوث تفريغ

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اضطراري لمستوى الماء في بحيرة السد للفترات (٨, ٢١، ٣٠) أيـــام محتمل حصولـــــــــه نتيجة استقرار جسم السد على صخور جبسية قابلة للذوبان. استخدم برنامج GEO-SLOP OFFECE في التحليل مع الأخذ بنظر الاعتبار الحالة المشبعة / غير المشبعة للتربة في التحليل. أظهرت نتائج التحليل إن قيم ضغط ماء المسام المتولد في لباب السد عند منسوب الماء الاعتيادي الموجود حاليا مقاربة للقيم الحقيقية المأخوذة من قراءات البيزومترات الموزعة على جسم السد. كما تم تسجيل قيم عالية لضغط ماء المسام لحالات التفريغ الاضطراري لحالة 8 أيام أكثر من الحالتين٢١،٣٠ يوم وخلال المقطعين الأول والثاني (sec6, sec4) المختارين أكثر من المقطع الثالث (sec2).

INTRODUCTION

Practicing engineering now is well aware that many of the problems they encounter in geotechnical engineering and construction involve unsaturated soils. Most of the engineering problems that involving heave, consolidation, collapse, and dramatic change in shear strength are directly related to the behavior of unsaturated soils.[1]

Dams is one of the important engineering structures that need a successful design, construction and requires a comprehensive knowledge of the characteristics of the site. The first step of the design and construction of dams is to obtain the details of the geotechnical investigations and the second step is a study of the physical and mechanical properties of the construction materials. The response of a typical earth dam subjected to an earthquake depends on many parameters such as, dam shape, the properties of materials, type and intensity of the motion, etc. Generally, the positive values of pore water pressure indicated of a fully saturated soil condition, while the negative value of the pore water pressure indicated that the soils are unsaturated.

Pagano et al (2006), studied the representativeness of measurement in the interpretation of earth dam behavior. The study is focused on the pore water pressure measurement; spatial continuity of pore water pressure is analyzed with consideration of both saturated and drained conditions. The paper discusses also, how pore water pressure can vary over the life time of the dam.[2]

Hosseini and Fard (2003) studied the influence of the impounding of the earth dams on the pore water pressure development with the core, while the construction is under progress. Special developed computer software (CA2) has been used to model and analyze the earth dam to determine the pore water pressure developing due to both impounding and constructing the dam at the same time. Pore pressure development through the clay core of an earth dam is difficult to analyze especially when the dam is multi-zones. So, finite element may be considered as the best tool for analysis.[3]

Pore water pressures may be modeled under a steady state or transient conditions, depending on the real situation. For example, if the reservoir level remains constant for a “long” period of time, a steady state pore water pressure could be used. On the other hand, in order to model pore pressures following dam impoundments, it is necessary to perform a transient state analysis.[4]

In this paper, A numerical analysis of pore water pressure development through the MOSUL dam is studied. The effect of the assumed earthquake is carried out, and also the pore water pressure developed within the clay core of the dam were investigated when the upstream water level are at the normal (310 m.a.s.l*), maximum (330 m.a.s.l), and minimum working state (300 m.a.s. l) with a possible of rapid drawdown of water which is represented the working ideal cases of the dam presently.

The possible enforce rapid drawdown will be studied due to water evacuation from reservoir (in case of emergency), since the dam foundation settle on sedimentary rocks and some of these rocks are gypsum rocks which is suffering from dissolution, considering three conditions "According to the river valley capacity downstream of the dam and the duration of evacuation of water from the reservoir", Taking all possible emergency conditions. The studied conditions are:

(i): normal condition within 30 days (no risk).

(ii): critical condition within 21 days (with some losses).

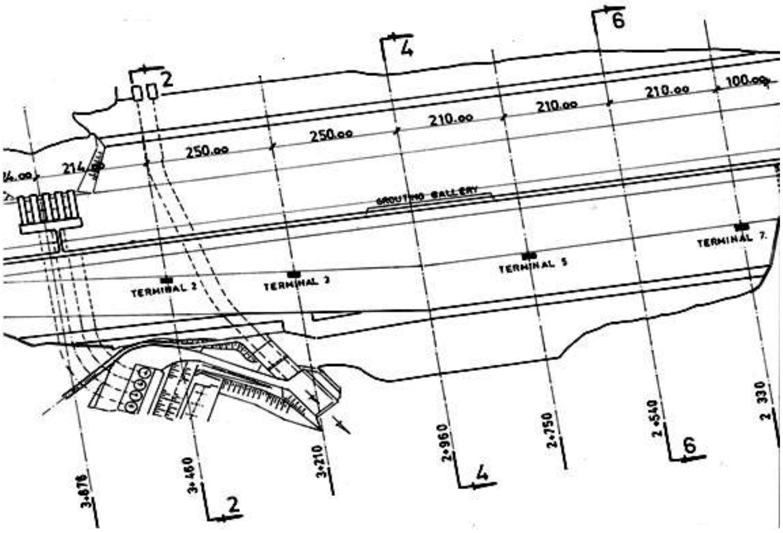
(iii): urgent condition 8 days. water evacuation time.

This conditions was supposed by S. A. A. Khattab., (2010) [1]. The analysis tool used to simulate pore pressure development is the GEO-SLOP OFFICE.

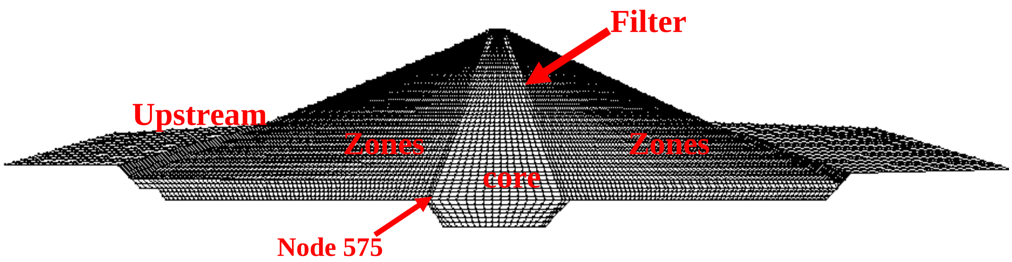
* m.a.s.l: meters above the sea level.

CHARACTERISTIC OF MOSUL DAM

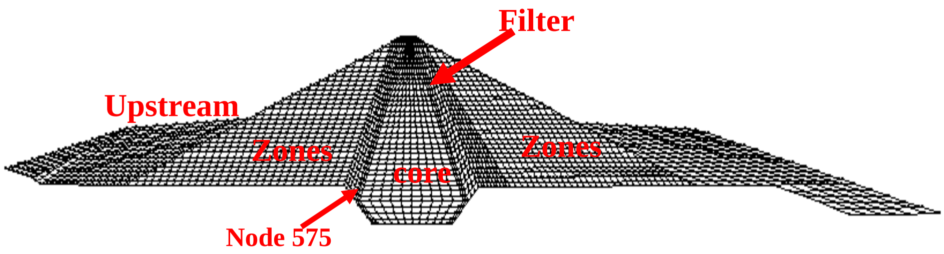
Mosul dam is an earth dam located on Tigris river about 50 Km north of MOSUL city / NINEVEH. The dam is about 3.6 Km long having approximately maximum height of 110 m with maximum retention level of 330 m above sea level. The construction of the dam was started in 1980 and lasted five years. The dam is situated on rock foundation, composed mainly of sedimentary rock. Some of these rocks (gypsum) seem to be relatively soft and suffering from dissolution. This should receive considerable attention. Figure (1) shows the plane and selected sections and also the finite element mesh used for the analysis. [5]



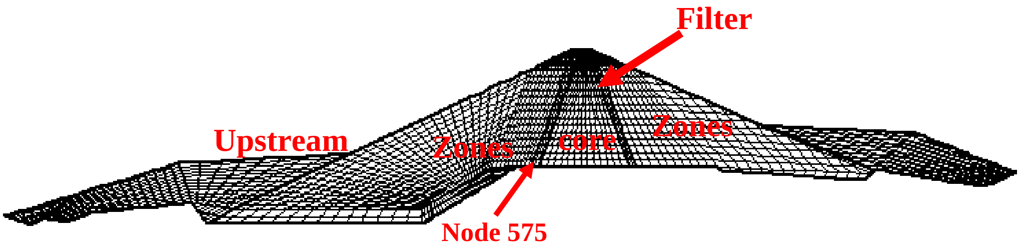
A) Plan of MOSUL dam[5].



(a): section 6



(b): section 4



(c): section 2

B) Selected Element Mesh

Figure (1) Plane and Cross-Sections with Element Mesh of MOSUL Dam.

The mesh includes four node quadrilateral elements. The boundary conditions at the base of the dam are assumed to be fixed in both vertical and horizontal directions. Material properties for the shell, filter, and core are shown in Table (1). The grain size distributions shown in Figure (2), soil water characteristic curves and conductivity functions were predicted using the program and depending on the Fredlund and Xing method.[9] .

Table (1) Materials Properties for the Study[5].

Parameters	Core			Filters	Rock fill shell
	Section2	Section4	Section6		
Natural density $\gamma(kN/m^3)$	20.86	21.4 37	21.331	20.42	22
Angle of internal friction Φ	19.75	22.5	26.56	47	45
Coefficient of earth pressure K_o	0.538	0.538	0.538	0.428	0.538
Cohesion c (kPa)	56.5	58.5	56.54	0	0
Modules of elasticity E (kPa)	22078.5	21500	33471	120000	200000
Hydraulic conductivity K (m/sec)	$3.741*10^{-11}$	$1.7*10^{-11}$	$5.014*10^{-11}$	$7.05*10^{-6}$	$5.5*10^{-5}$

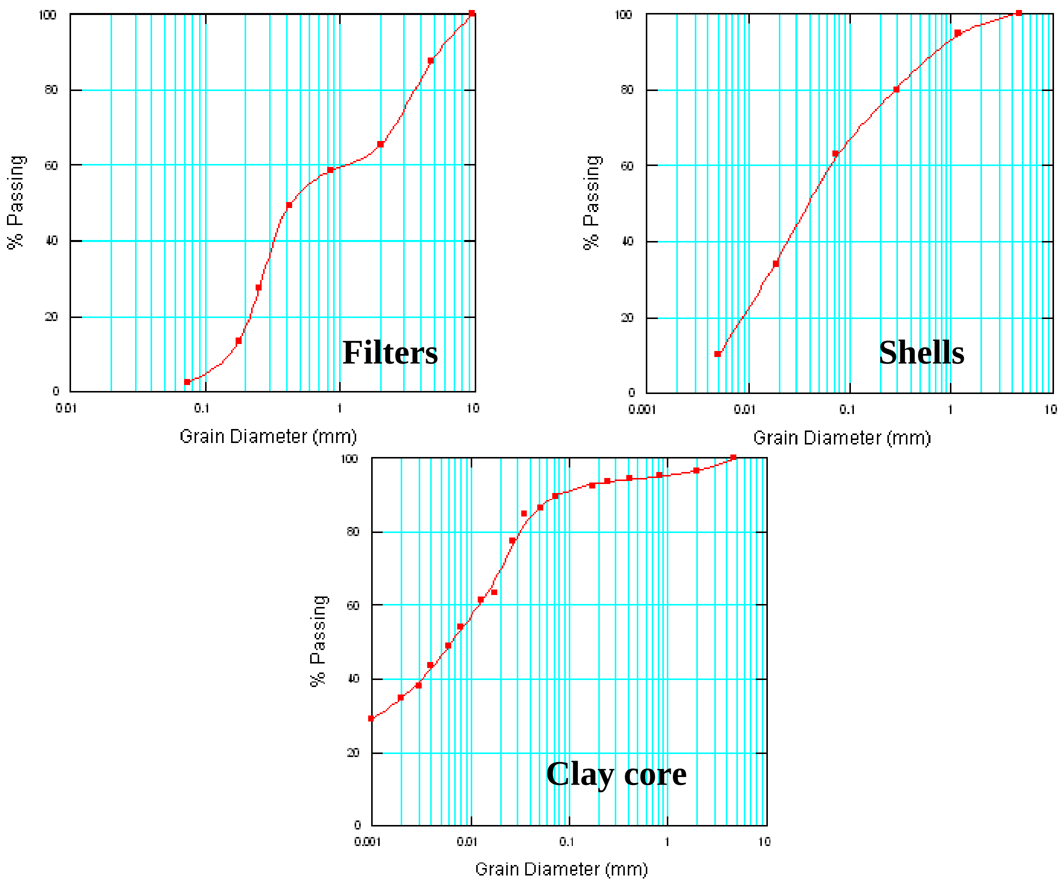


Figure (2) Grain size distribution for soils used.[5].

THEORY

A. Seepage Analysis: SEEP/W is formulated on the basis that the flow of water through both saturated and unsaturated soil follows Darcy's low which states that:[6][1]

$$q = k * i \qquad \ldots(1)$$

Where: q is specific discharge in m^3/sec; k is hydraulic conductivity; i is gradient of fluid head.

Darcy's low was originally derived for saturated soil, but later researches Fredlun, D. G. and Rahardjo H. [7] were shown that it can also be applied to the flow of water through unsaturated soil.

The governing differential equation used in the formulation of SEEP/W is:[6]

$$\frac{\partial}{\partial_x}\left(k_x \frac{\partial H}{\partial_x}\right) + \frac{\partial}{\partial_y}\left(k_y \frac{\partial H}{\partial_y}\right) + Q = \frac{\partial \theta}{\partial_t} \qquad \ldots(2)$$

Where H is total heads k_x & k_y are hydraulic conductivity; Q is applied boundary flux; θ is volumetric water content; and t is time.

Under steady-state condition the equation reduces to:

$$\frac{\partial}{\partial_x}\left(k_x \frac{\partial H}{\partial_x}\right) + \frac{\partial}{\partial_y}\left(k_y \frac{\partial H}{\partial_y}\right) + Q = 0 \qquad \ldots(3)$$

The stress state for both saturated and unsaturated conditions can be described by two variables. The first: stress state variables are pore-air pressure ($-u_a$) and matric suction (u_a-u_w) where; u_a is the pore-air pressure, and u_w is the pore-water pressure.

The second assumption is that the pore-air pressure remains constant at atmospheric pressure during transient processes. This means that the formulation in terms of effective stress (σ-u_w) remains constant and has no effect on the change in volumetric water content; where σ is total stress, and u_w is the pore-water pressure. Changes in volumetric water content are consequently depend only on the matric suction (u_a-u_w) stress state variable, and with u_a remaining constant, the change in volumetric water content is a function only of pore-water pressure changes.

A change in volumetric water content can be related to a change in of pore-water pressure by the equation:

$$\partial\theta = m_w \, \partial u_w \qquad \ldots(4)$$

where m_w is the slope of the storage curve.

The total hydraulic head is defined as:

$$H = \frac{u_w}{\gamma_w} + y \qquad \ldots(5)$$

where u_w is the pore-water pressure; γ_w is unit weight of water; y is elevation.

$u_w = \gamma_w \times (H-y)$, by substitution into Equation (2).

$$\frac{\partial}{\partial_x}\left(k_x \frac{\partial H}{\partial_x}\right) + \frac{\partial}{\partial_y}\left(k_y \frac{\partial H}{\partial_y}\right) + Q = m_w\ \gamma_w \frac{\partial (H-y)}{\partial_t} \qquad \ldots(6)$$

Since the element is constant:

$$\frac{\partial}{\partial_x}\left(k_x \frac{\partial H}{\partial_x}\right) + \frac{\partial}{\partial_y}\left(k_y \frac{\partial H}{\partial_y}\right) + Q = m_w\ \gamma_w \frac{\partial H}{\partial_t} \qquad \ldots(7)$$

B. Quake Analysis: The governing motion equation for dynamic response of a system in finite element formulation can be expressed as:[9]

$$[M]\,\{\ddot{a}\} + [D]\{\dot{a}\} + [K]\{a\} = \{F\} \qquad \ldots(8)$$

where [M] mass matrix; [D] damping matrix; [K] stiffness matrix; $\{\ddot{a}\}$ vector of nodal acceleration; $\{\dot{a}\}$vector of nodal velocities; $\{a\}$vector of nodal displacement. The vector of loads could made up by different forces:

$$\{F\} = \{F_b\} + \{F_s\} + \{F_n\} + \{F_g\} \qquad \ldots(9)$$

where: $\{F\}$ is vector of load; $\{F_b\}$ body force; $\{F_s\}$ force due to surface boundary pressure; $\{F_n\}$ concentrated nodal force; and $\{F_g\}$ earthquake loads.

The mass matrix can be a consistent mass matrix or lumped mass matrix. The consistent mass matrix:

$$[M] = \int_v \rho \langle N\rangle^T \langle N\rangle\, d_v \qquad \ldots(10)$$

Damping matrix assume to be a linear combination of mass matrix and stiffness matrix:

$$[D] = \alpha\,[M] + \beta\,[K] \qquad \ldots(11)$$

where α & β are scalars and called Rayleigh damping coefficients.

The stiffness matrix is:

$$[K] = \int_v [B]^T\,[C]\,[B]\,d_v \qquad \ldots(12)$$

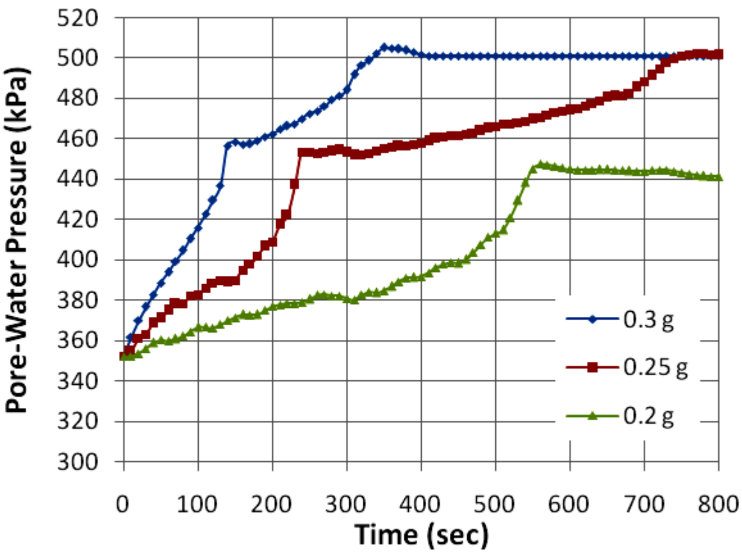
Where [B] is strain displacement matrix; [C] constitutive matrix

RESULTS AND DISCUSSIONS

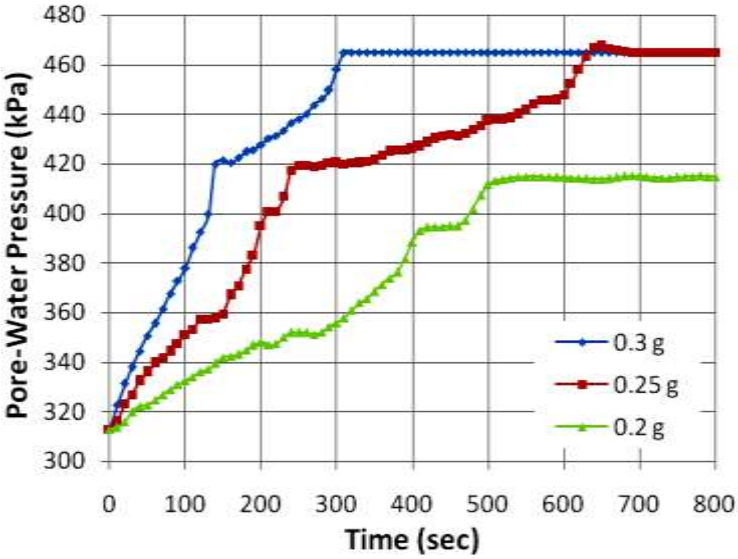
A. Pore water pressure response when an earthquake accrue within MOSUL dam:

Dynamic analysis of MOSUL dam was performed using transient saturated-unsaturated seepage output model. The earthquake recorded for 30 sec corresponds to an acceleration of 0.3g-0.2g this values take up according to Marcuson, W. F., (1981) and Hynes-Griffin, M. E., and Fraklin, A. G., (1984). [8]

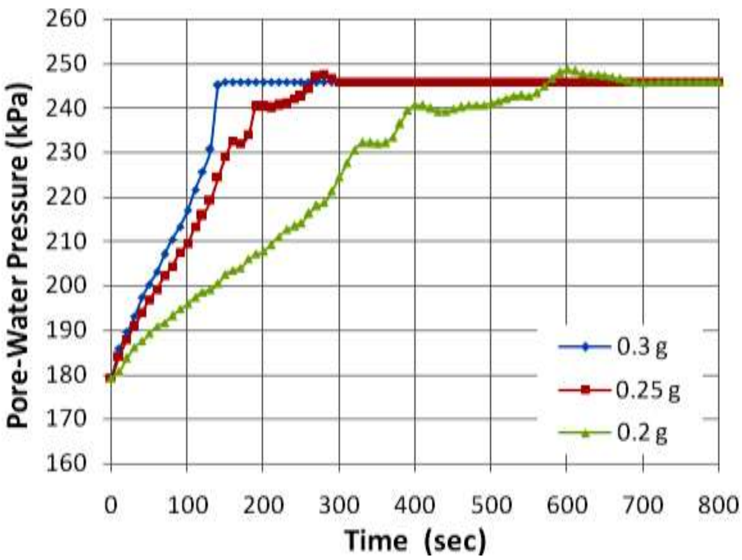
Figure (3) shows the results of the pore water pressure influence due to the earthquake on MOSUL dam with maximum acceleration ranges between (0.2g - 0.3g). The pore water pressure was predicted in the upstream near the core at nodes (575) for Sec6, Sec4, and Sec2 respectively) as shown in Figure (1). The analysis time used in the study was assumed to be (800 sec), for a (30 sec) period earthquake to investigate the behavior of the soil at the beginning, during, and after the end of the earthquake. It is shown that the pore water pressure increases at the time after earth quake take place reaching the values (505.02 kPa at time 340 sec), (464.92 kPa at time 300 sec), and (245.86 kPa at time 150 sec) for Sec6, Sec4, and Sec2 respectively, when the maximum horizontal acceleration is (0.3g). Same results could be obtained for the other assumed horizontal acceleration of (0.25g, and 0.2g).



a): sec6



b): sec4



c): sec2

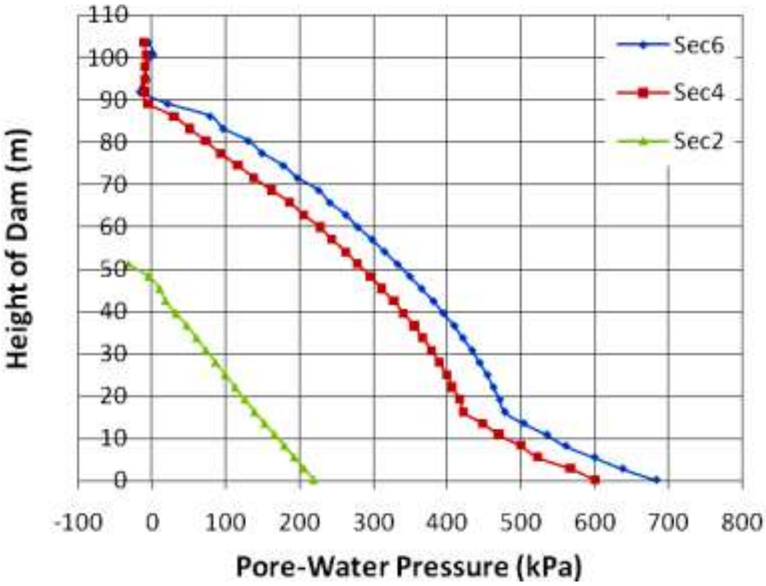
Figure (3) Pore water pressure developing during and after earthquake.

The maximum pore water pressure was occurred at time more than 120 sec (higher than the shaking time of 30 sec) and not at the time of earthquake. Perhaps this is due to redistribution of pore water pressure within the dam body which is depend on many factors such as the permeability of the core and zones. Also the earthquake occurs over a period time that is very short when it compared with the characteristic time scale for pore water pressure distribution.

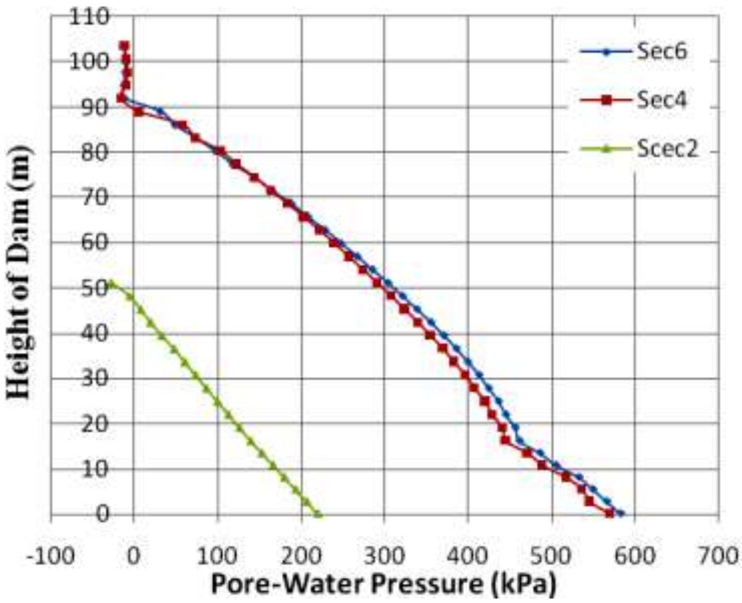
B. Pore water pressure during possible rapid drawdown in water elevation

The results of the pore water pressure during the assumed rapid drawdown in water level at time (8, 21, 30) days through the cross section A-A for the three selected sections sec6, sec4, and sec2 as illustrated in Figure (1) is presented in Figure (4). It could be noted that the time of the drawdown of water affects on the values of pore water pressure development. High values of the pore water pressure were founded at the end of 8 days time. More values of pore water pressure developing where recorded through sections 6 & 4.

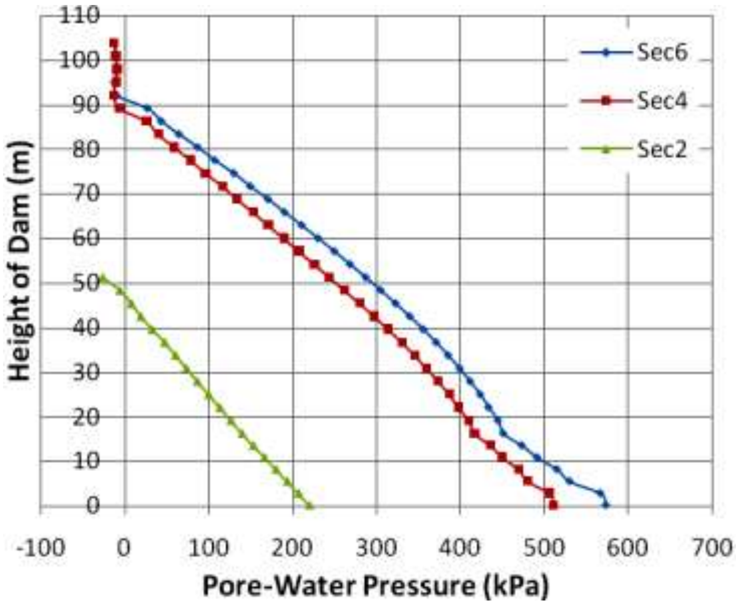
Results show that the pore water pressure developed values at the base was ranges between (583-510 kPa) for sec6 and sec4 at time 21 and 30 days while it ranges between (683-601 kPa) at time 8 days. This may due to the pore water pressure cannot dissipate in a suitable fast way as rapid drawdown of water level occurs to the water level. The dissipation of pore water pressure during rapid drawdown is depended on the permeability and storage attribute of the dam materials. Small size of sec2 give adjustable value of pore water pressure (220 kPa) for all the possible rapid drawdown considering condition.



a): 8 days



b): 21 days



d): 30 days

Figure (4): Pore water pressure development during rapid drawdown water

C. Pore water pressure when the water at normal, maximum, and minimum operation levels:

The analysis of pore water pressure distribution through the clay core of MOSUL dam is presented in figures (5 to 7).

Figure (5) summarize the values of pore water pressure variation within the core when the reservoir water is at the maximum operation level (330 m.a.s.l) for the three selected sections. Results show that the developed values for pore water pressure at the base of the core is about (445-431 kPa) for both sec4 and sec6, and (190 kPa) for sec2.

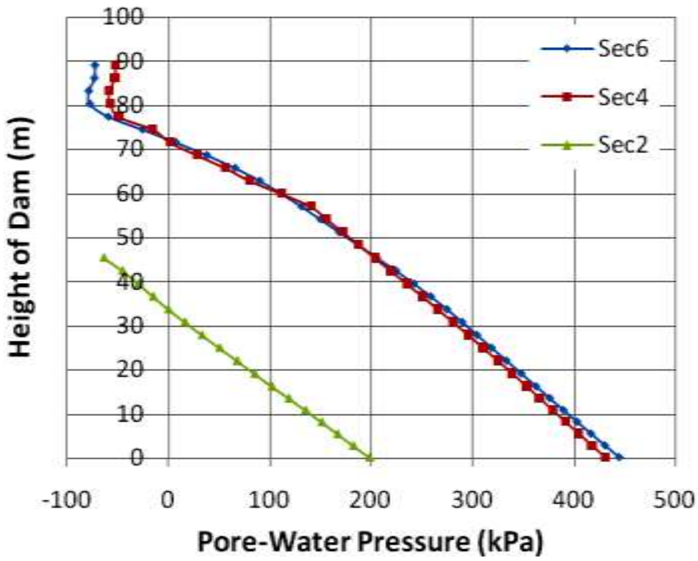


Figure (5) Pore water pressure develop for the reservoir water is at the maximum level.

Figures (6) and (7) illustrate the pore water pressure distributions in the core for the selected sections when the reservoir water is at the normal (310 m.a.s.l), and minimum (300 m.a.s.l) operation level. Small values of the developed pore water pressure were recorded through sec2 (167-34. kPa) for normal and minimum reservoir level. While higher values (402-407 kPa) and (299-293 kPa) respectively for normal and minimum reservoir level were recorded at the base of sec6 and sec4. This is due to the height variation of the earth dam which is affected on the pore water pressure distributions.

It could be noted from the figures also that the largest positive pore water pressure is occurred at the base of the core (saturated zone). These values decrease slightly as moving away from the base towards the crest of the dam (as a suction in un saturated zone).

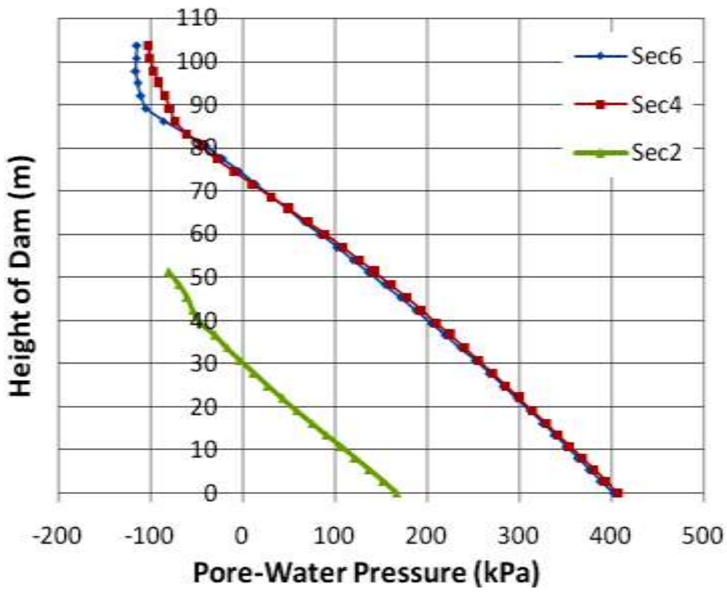


Figure (6) Pore water pressure develop for the reservoir water is at the normal level.

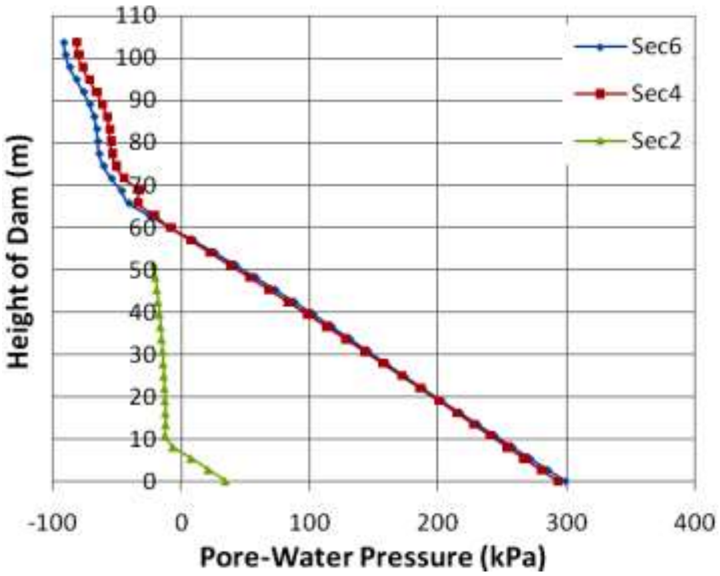


Figure (7) Pore water pressure develop for the reservoir water is at the minimum level.

The finite element results of the pore water pressure for both sec6 and sec4 when the water at the normal reservoir operation level (310 m.a.s.l) as shown in Figure (6) were compared with the recorded field piezometers readings at years 2006 as shown in Figure (8). It could be concluded that the field value of the pore water pressure seems to be the same as that obtained from numerical studied results.

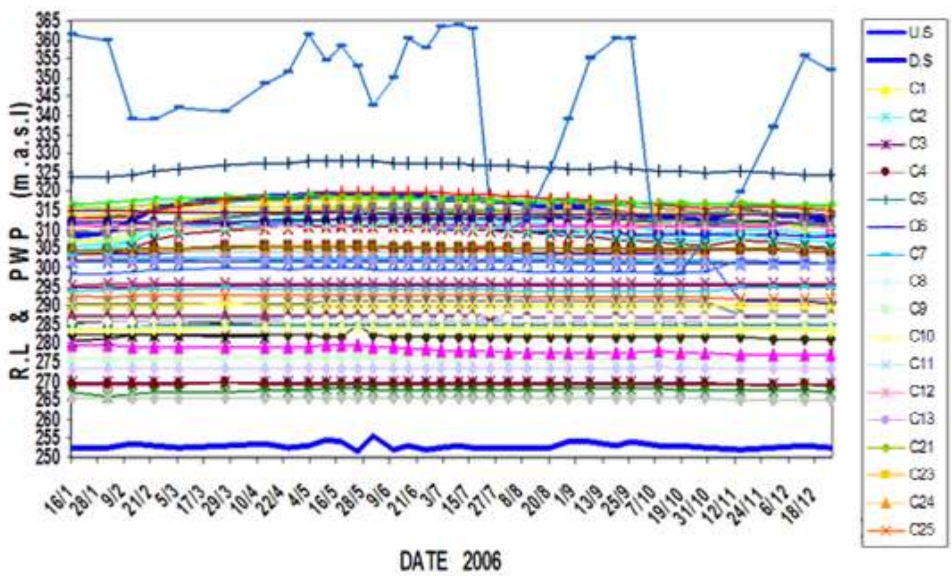


Figure (8) Pore water pressure from available piezometers readings.

CONCLUSIONS

From the analysis of pore water pressure of MOSUL dam, the following conclusions could be obtained:

1. The maximum pore water pressure was found to be on the node at upstream near the core base at a time exceeding the earthquake shaking time.
2. The highest positive pore water pressure occurred within the lowest part of the core, and it's obtained for the 8 days rapid drawdown case, for both sections sec6 and sec4. On the other hand, the pore water pressure is nearly identical for the all rapid drawdown sec2.
3. Similar behaviors of pore water pressure are developed in the core when the water level is at maximum and minimum elevations. Positive values within the lower part of the core and negative in the upper part of the core.
4. The pore water pressure results at the base of the core, obtained from the finite element analysis, for both sections sec6 and sec4, are nearly identical to that obtained from the available field piezometers readings at year 2006.

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