Numerical Modeling of Pore Water Pressure Development within a Thin Clay Core in an Earth Dam

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Abstract

This work aims at studying the pore water pressure development within a thin clay core in an earth dam. The study consists of two parts; a parametric study for general thin clay core (with and without chimney drains), followed by a case study of BADUSH dam. Different operation levels and storage times with the possibility for rapid rise in water level are considered for the case study. Finally the effect of an earthquake on pore water pressure in this types of a dam was also studied as a case study.

Two dimensional finite element analysis was used to simulate pore water pressure development by GEO-SLOP software taking into consideration saturated /unsaturated conditions. Results showed that the presence of a chimney drain plays an effective role in dissipation of the pore water pressure. In the case of BADUSH dam, a high pore water pressure development was observed, in 8 days as a consequence of a rapid rise of water level, and it must be taken into account when designing dams. Also results show that the pore water pressure in the range of (175-145 kPa) through the typical section and approximately between (25-50 kPa) for the two other sections at the end of construction time, making the height and construction time of the dam are the most effective factors affecting pore water pressure development.

Keywords: Pore water pressure, Finite element, Unsaturated soil, BADUSH dam.

دراسة نظرية لضغط ماء المسام المتولد في لباب سد ترابي رقيق السمك

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الخلاصة

يهدف البحث الحالي إلى دراسة ضغط ماء المسام المتولد في لب السد خلال مراحل الإنشاء وأثناء عمليات الخزن أو حدوث ارتفاع في منسوب الماء خلال فترة قصيرة. يتكون البحث من جزئيين لدراسة ضغط ماء المسام: الجزء الأول تطرق إلى دراسة تأثير وجود فلتر عمودي خلال مقطع عام لسد ترابي مع الأخذ بنظر الاعتبار تأثير حالتي التربة المشبعة وغير المشبعة في الدراسة. أما الجزء الثاني فتمثل بدراسة ضغط ماء المسام المتولد خلال سد بادوش بثلاث مقاطع خلال مراحل الإنشاء وما بعد مراحل الإنشاء في حال حدوث ارتفاع مفاجئ لمستوى الماء لفترات (8، 21، 30، 183) يوم. كما تم دراسة ضغط ماء المسام في السد عندما يكون الماء في أعلى وأوطأ مستوى تشغيلي للفترات (1، 5، 10) سنة، مع الأخذ بنظر الاعتبار أيضا احتمالية حدوث هزة أرضية خلال حالات ارتفاع مستوى الماء في المقطع الأول. من النتائج التي تم الحصول عليها إن وجود الفلتر العمودي ذو تأثير فعال في تقليل ضغط ماء المسام. كما أظهرت النتائج أن لارتفاع السد والوقت المستغرق في إنشاء السد تأثير على قيم ضغط ماء المسام حيث تراوحت قيم ضغط ماء المسام بمدى (175-145 kPa) خلال المقطع الاساسي وبمدى (25-50 kPa) للمقطعيين الاخرين، فضلا عن أن حدوث الارتفاع المفاجئ لمستوى الماء خلال فترات زمنية قليلة يؤدي إلى تطور ضغط ماء المسام بشكل كبير مقارنة بباقي الفترات المحتملة حدوث الارتفاع المفاجئ للماء.

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Introduction

Sensitive structures, such as earth dams, require continuous information on their stability. Engineers must estimate the movement, stress-strain, and pore water pressure which could be developed in an earth dam at various times of its life. [1]

Safety of earth dam depends on the proper design, construction, and monitoring of actual behavior during the construction and during the operation of the structure. [2]

The pore water pressure starts developing within the clay core in some stages of filling due to increased the height of the dam. Usually large pore water pressure will develop within the core when more than half of the dam height is constructed due to consolidation process [3]. The development of high pore pressures and possibility of liquefaction either in the foundation or earth dam during earth quakes may cause failure of an earth dam.[4]

For thin clay core dams, the drawdown pressure might be negative. In this type of earth dams, the core may be sloped upstream or placed in a vertical position near the center of the earth dam. The pervious zones are constructed either of sand and gravel or of rock, obtained by quarrying or screening earth-rock mixtures. A vertical drain (chimney), if available will be constructed to about 70% of the dam height in order to collect water from the dam body.[1]

The finite element method is practical and applicable in many geotechnical engineering topics. Finite element method may be used to predict pore water pressure development with or without possibility of seismic behavior through earth dam which is difficult to be analyze especially in the multi-zones dams.

Hosseini and Fard (2003) studied the influence of the impounding of the earth dams on the pore water pressure development within the core. Using a special computer software (CA2). [3], While Abbasi et al(2006) discussed numerical dynamic analysis of Sonnateh dam body located on an active fault, the analysis performed by GEO-SLOPE and ANSYS finite element programs. [5]

Moayed and Ramzanpour (2008) investigated the seismic behavior of a zoned core embankment dam in two cases including homogenous clayey and zoned core by finite element soft ware. The study shows the displacement, accelerations and spectral response in a simple core are more than a zoned core.[6]

This work aims at studying the pore water pressure development within a thin clay core in an earth dam. Two dimensional finite element methods for saturated /unsaturated analysis were conducted using GEO-SLOP Version 5 software.

To investigate the pore water pressure development the study consists of two parts: the first is a parametric study for general thin clay core and the second is a case study for BADUSH dam, with the following assumption for both parts:

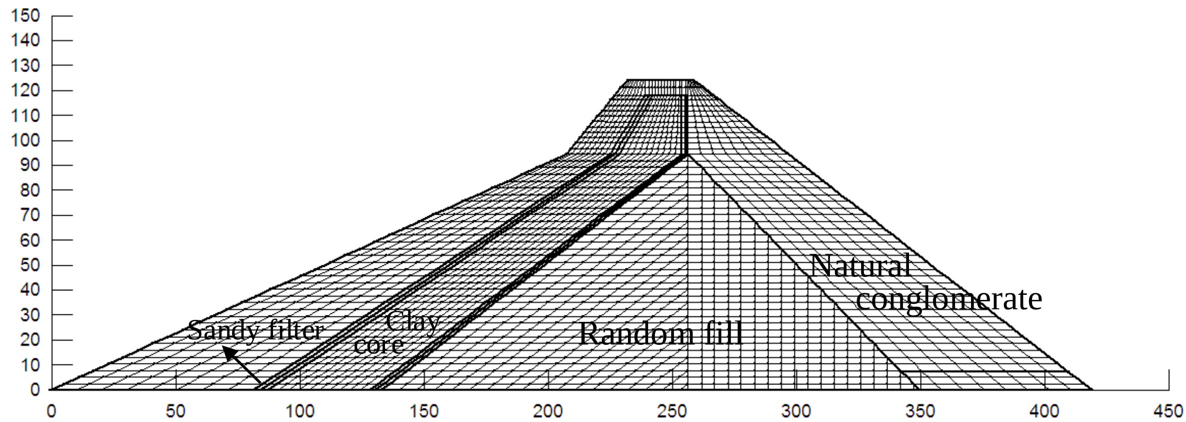
1. Earth dam constructed on impermeable hard stratum.
2. There is no flow through the base of the dam.
3. Earthquake record taken from available information about last earthquake tremor that took place in MOSUL city on 18/7/2009.

The specific objectives of the case study are to obtain the pore water pressure development within the clay core for selected section in :

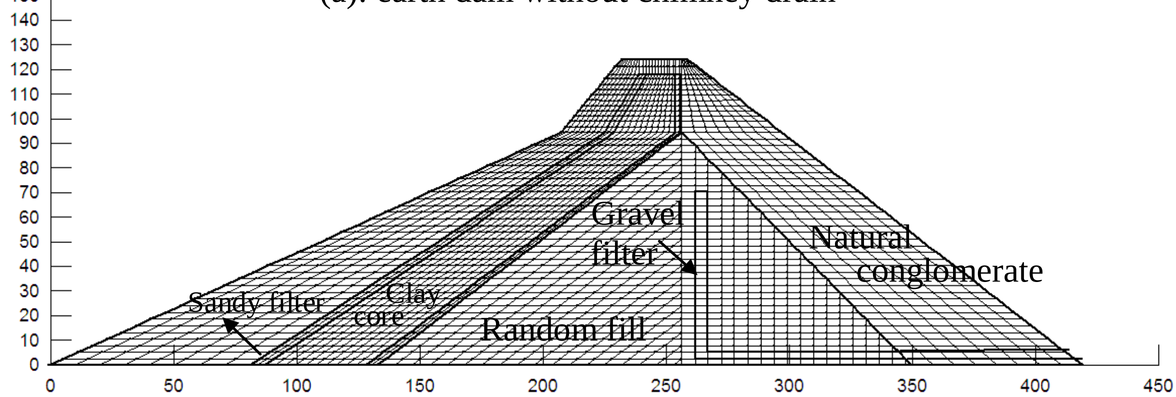
1. Different assumed construction stages time.
2. Effect of a possible rapid rise of water level.
3. Different retention of water level.
4. The effect of Possible earthquake tremor on the earth dam during rise of water level.

Parametric study

The parametric study consists of two sections: first is to investigate the effect of presence of a chimney drain on the pore water pressure development through a typical section of an earth dam with a thin clay core, while the second is to study the effect of considering an unsaturated soil of the dam and compare it with that of classical saturated condition. A typical dam was studied with the maximum height of an earth dam from the crest to foundation level is (120m). Downstream slope is considered to 1V:2.2H and 1V:1.3H in upstream as shown in Figure (1) , **<u>Not:</u>** all dimensions are in meter.



(a): earth dam without chimney drain



(b): earth dam with chimney drain

Figure (1): Cross sections of the earth dam for the parametric study. [1]

Case study

BADUSH dam is an earth fill dam under construction located on the Tigris River 15 km north west of MOSUL city / Nineveh and about 40km south of MOSUL dam as shown in Figure (2). It is especially designed to retain eventual a catastrophic flood which could occur from MOSUL dam failure and to protect MOSUL and the downstream cities.

The maximum embankment height measured from the crest to the clay bottom core trench is (95m) for typical section (section1), and (50, 35m) for the two other sections (section2, and section3). Figure (3) shows the geometry of the dam in three sections. Downstream and upstream slopes are inclined by 1V:2H, and 1V:2.5H respectively, **<u>Not:</u>** all dimensions are in meter..

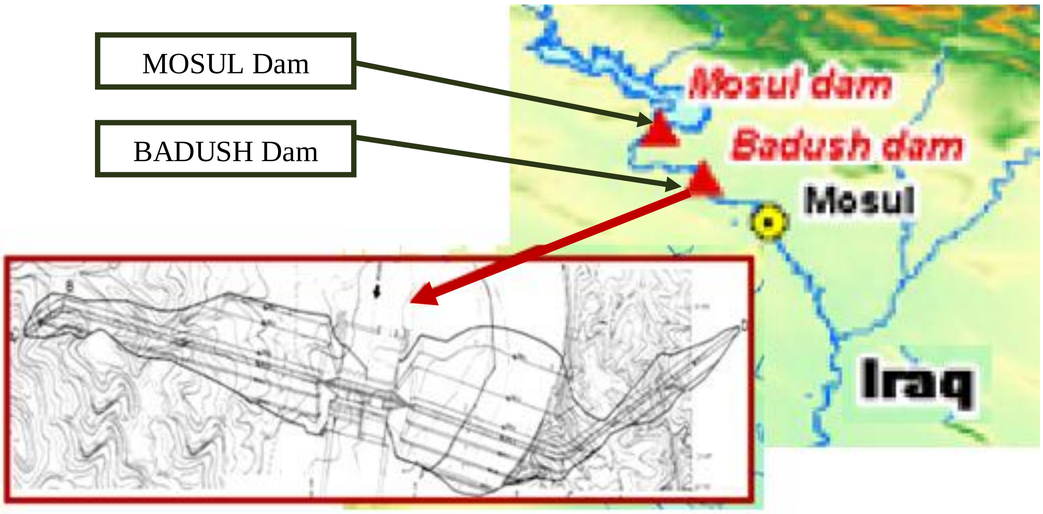
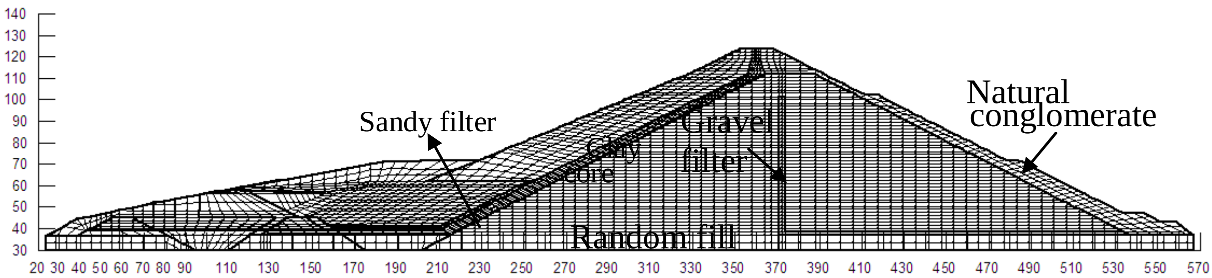
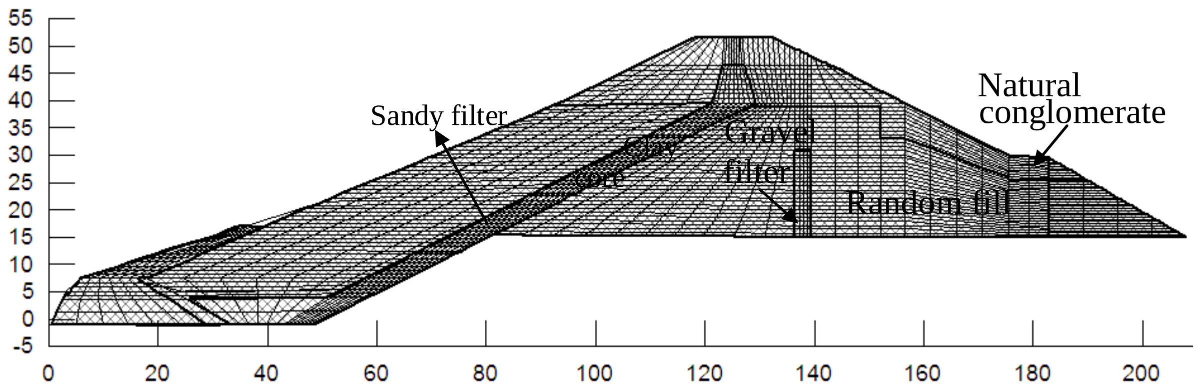


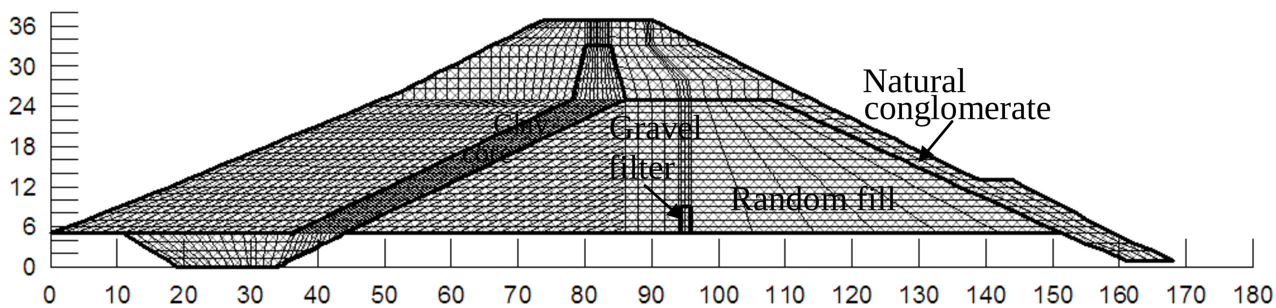
Figure (2): BADUSH Dam Location



(a): Section1



(b): section2



(c): section3

Figure (3): Cross sections of the BADUSH dam for the case study. [7]

Material properties and analysis method

BADUSH dam project report provides filters, and clay core materials properties as illustrated in table (1). Grain size distributions of the selected soils used are demonstrated in Figure (4). Conductivity functions and soil water characteristic curves for the soils used are predicted using Fredlund's and Xing method are shown in Figures (5) and (6).

The discretisation of parametric and case studies of dams cross sections for the finite element solutions are performed by rectangular four nodes with four degree of integration elements scheme. The boundary conditions on the nodes are assumed to be fixed in both horizontal and vertical directions. For the case study the dam is under construction at the present time, there is no piezometric reading so the pore water pressure values were taken from the theoretical study using (SEEP/W & SIGMA/W). .

Rapid rise in water level at times of (8, 21, 30 days) was supposed for the reason of a possible critical case of rapid drawdown of water in MOSUL dam and may occurred at three time conditions: [8]

i): Normal conditions time (30 day).
ii): Critical conditions time (21 day).
iii): Urgent conditions time (8 day).

The QUAKE/W finite element software was also used for the dynamic analysis. The dam has been analyzed first under static conditions, then seismic studies will be conducted to model the dynamic analyses of the dam during the earthquake loading. The analysis was conducted at the end of time of rising water level (8, 21, 30) days. The time of the analysis was taken as 6 sec with Δt=0.001 sec.

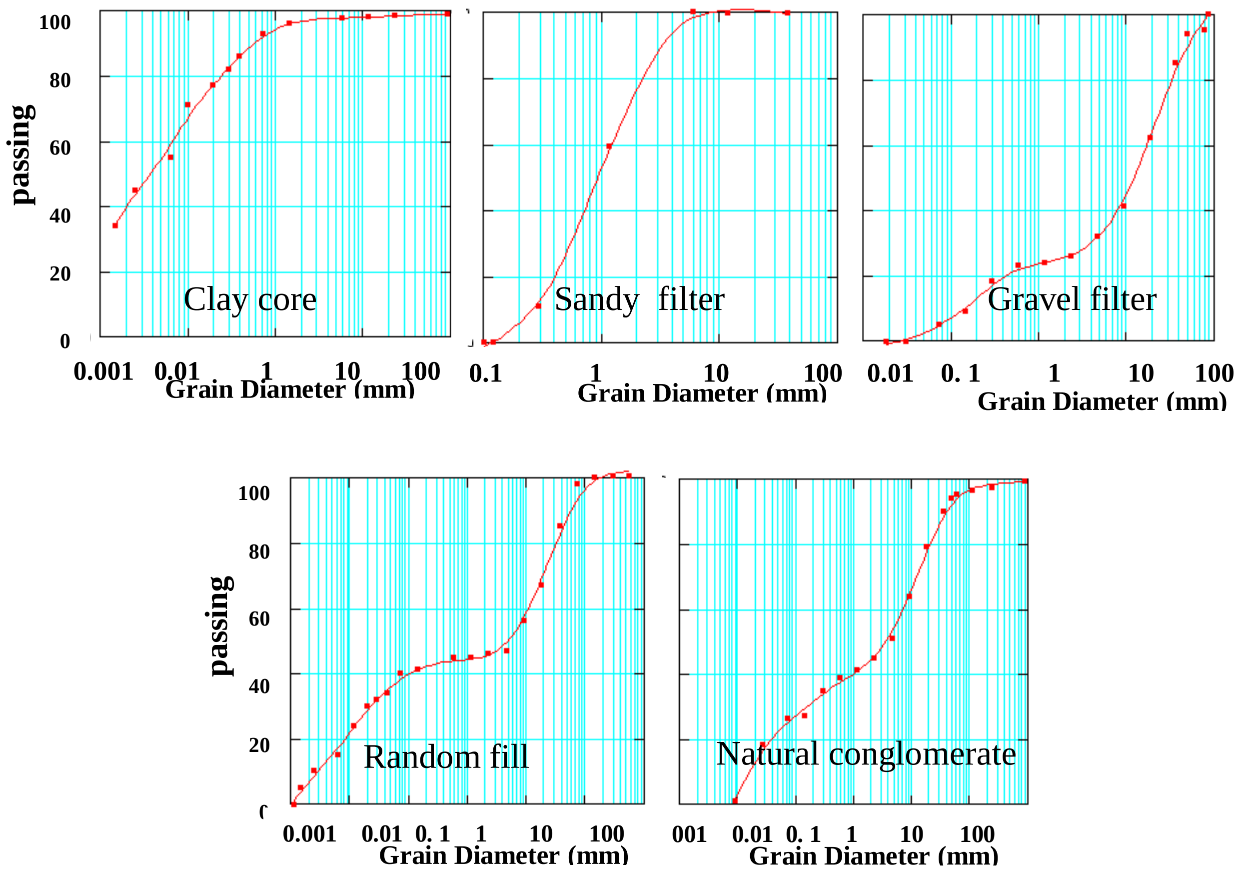


Figure (4): Grain size distribution for soils used.[8]

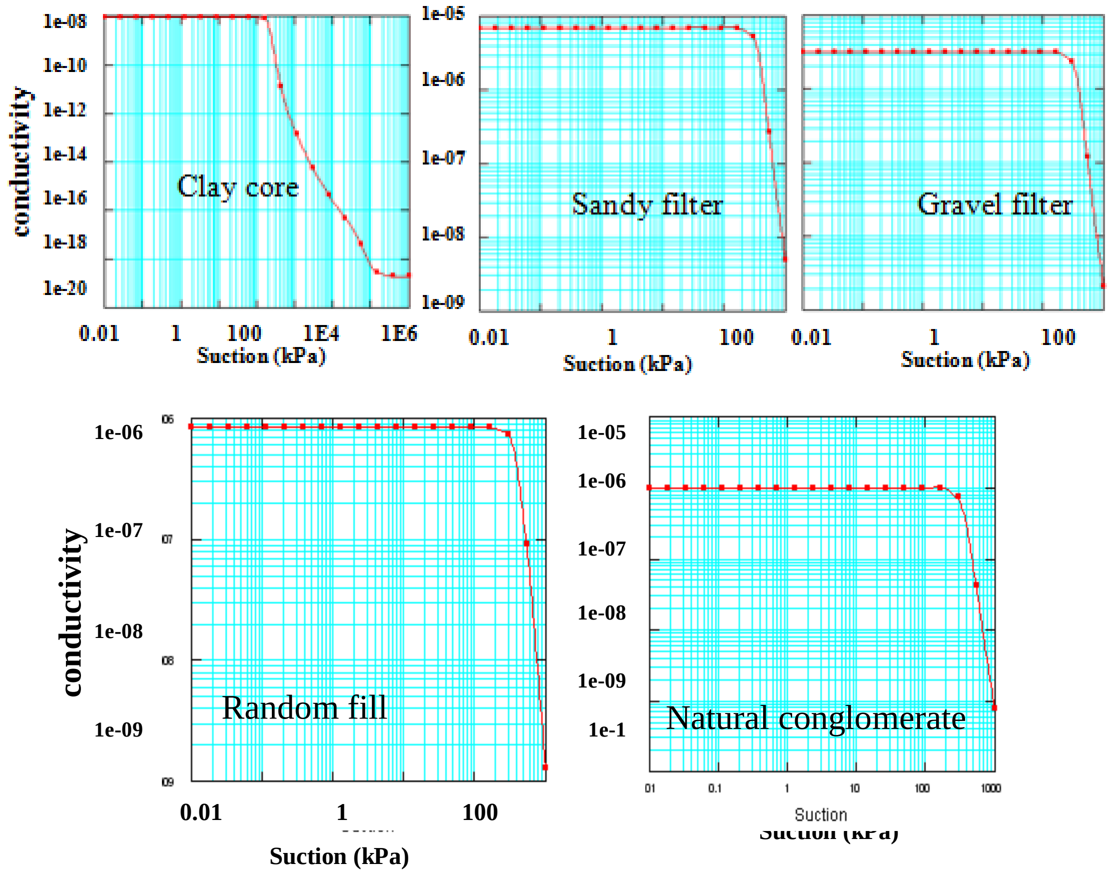


Figure (5): The Predicted Conductivity functions for soils

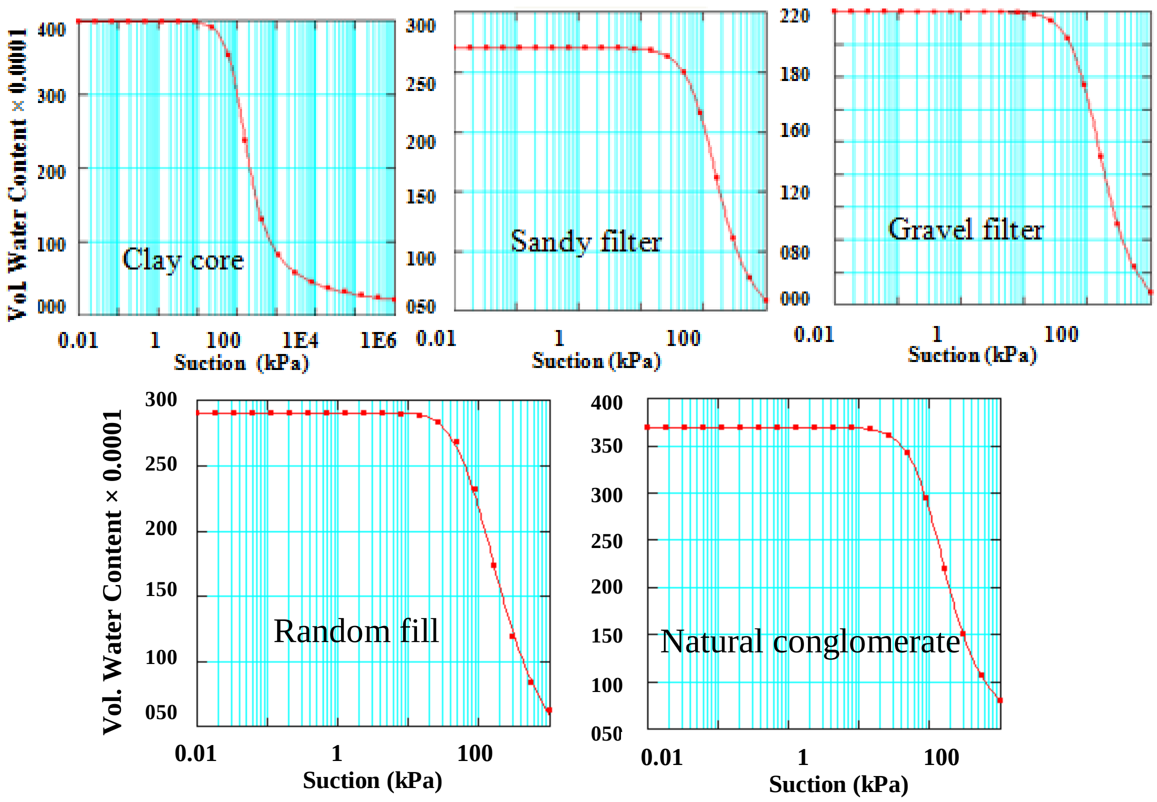


Figure (6): The Predicted Soil water characteristic curves for soils

Results and Discussions
Parametric study

Figure (7) shows a comparison between the classical case " saturated" and that considering the unsaturated part of the dam on the estimation of the pore water pressure developing within the dam section, when the water level is at the maximum level after one year, considering a dam with a chimney drain. The results of the final steps for the analysis show that the values of pore water pressure developing in the saturated condition are more positive value in the lower part and less negative value in the upper part of the core.

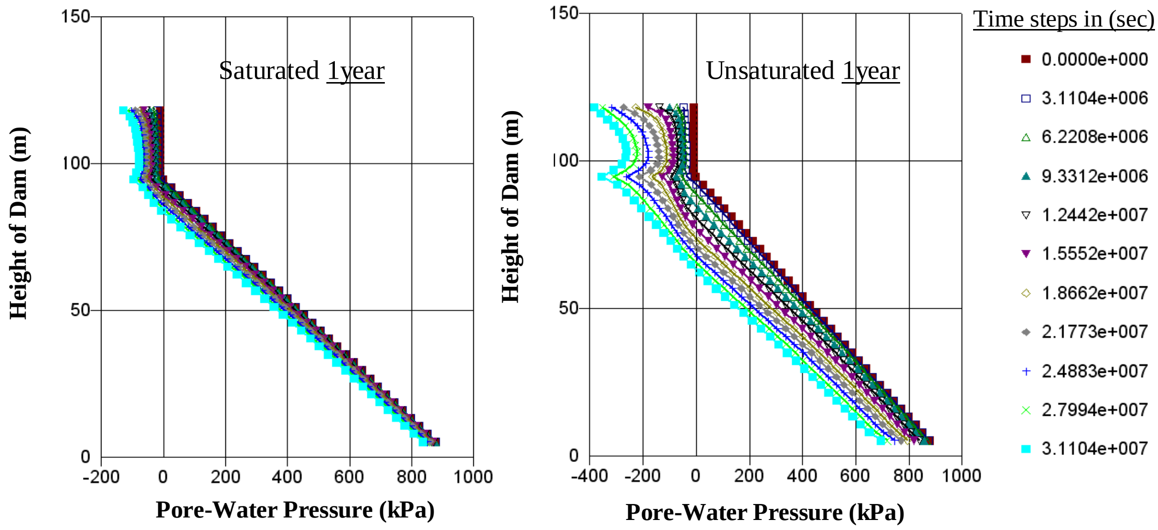


Figure (7): Pore pressure development for parametric study at maximum level for saturated / unsaturated conditions

Figure (8) summarizes the value of pore water pressure variations within the core of the section in two cases (with and without chimney drain) for three different selected times chosen as (4, 6, 12 months) for water retention when the water level is taken at the maximum level. The results show slightly more pore water pressure development in the section without chimney with respect to that with a chimney. This could be explained as: " the chimney provides vertical strip of earth dam with zero pore water pressure in the central portion of the dam", [1] and pore water pressure in the case without a chimney may not dissipate immediately.

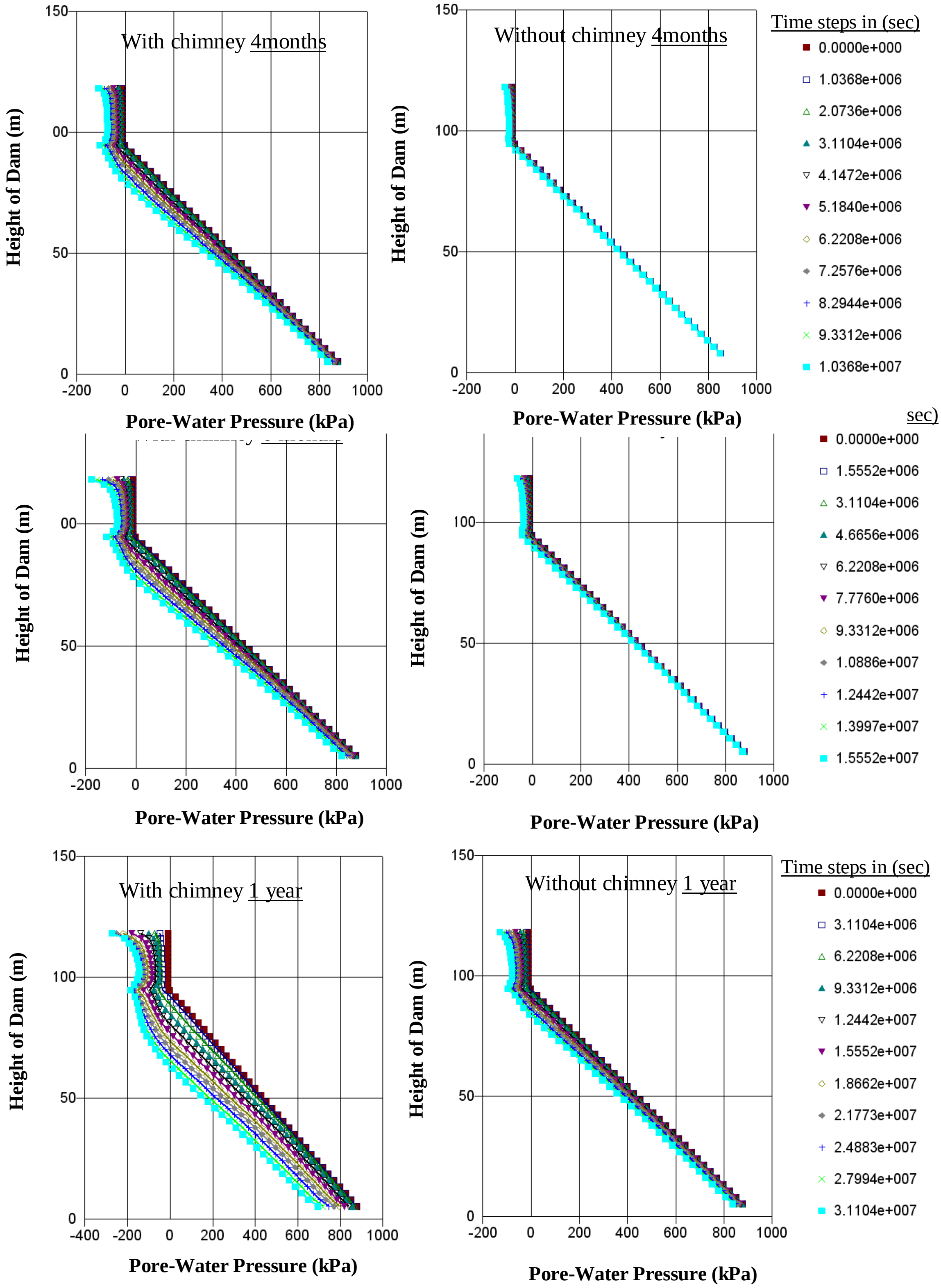


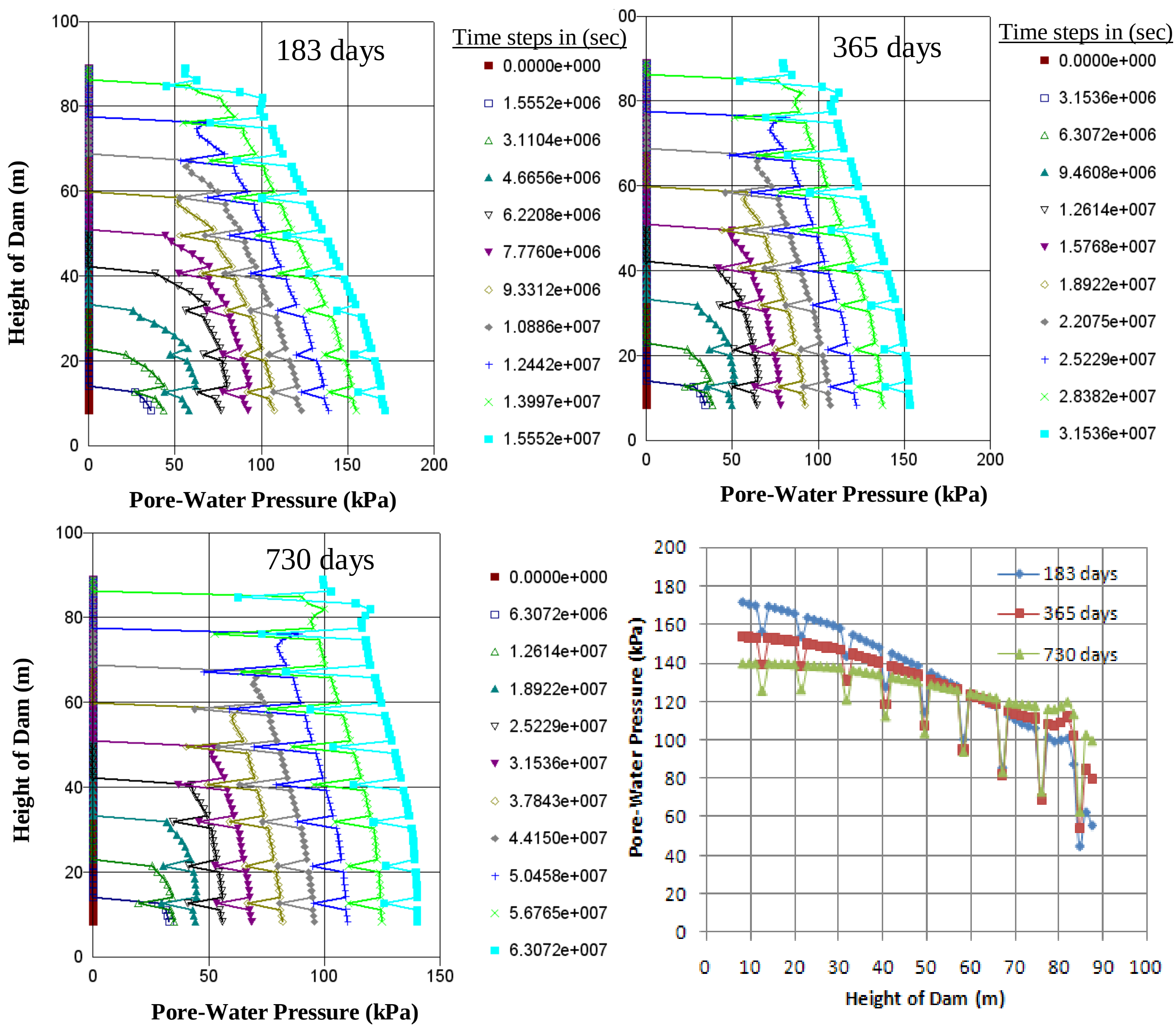
Figure (8): Pore pressure development for parametric study at maximum level

Case study

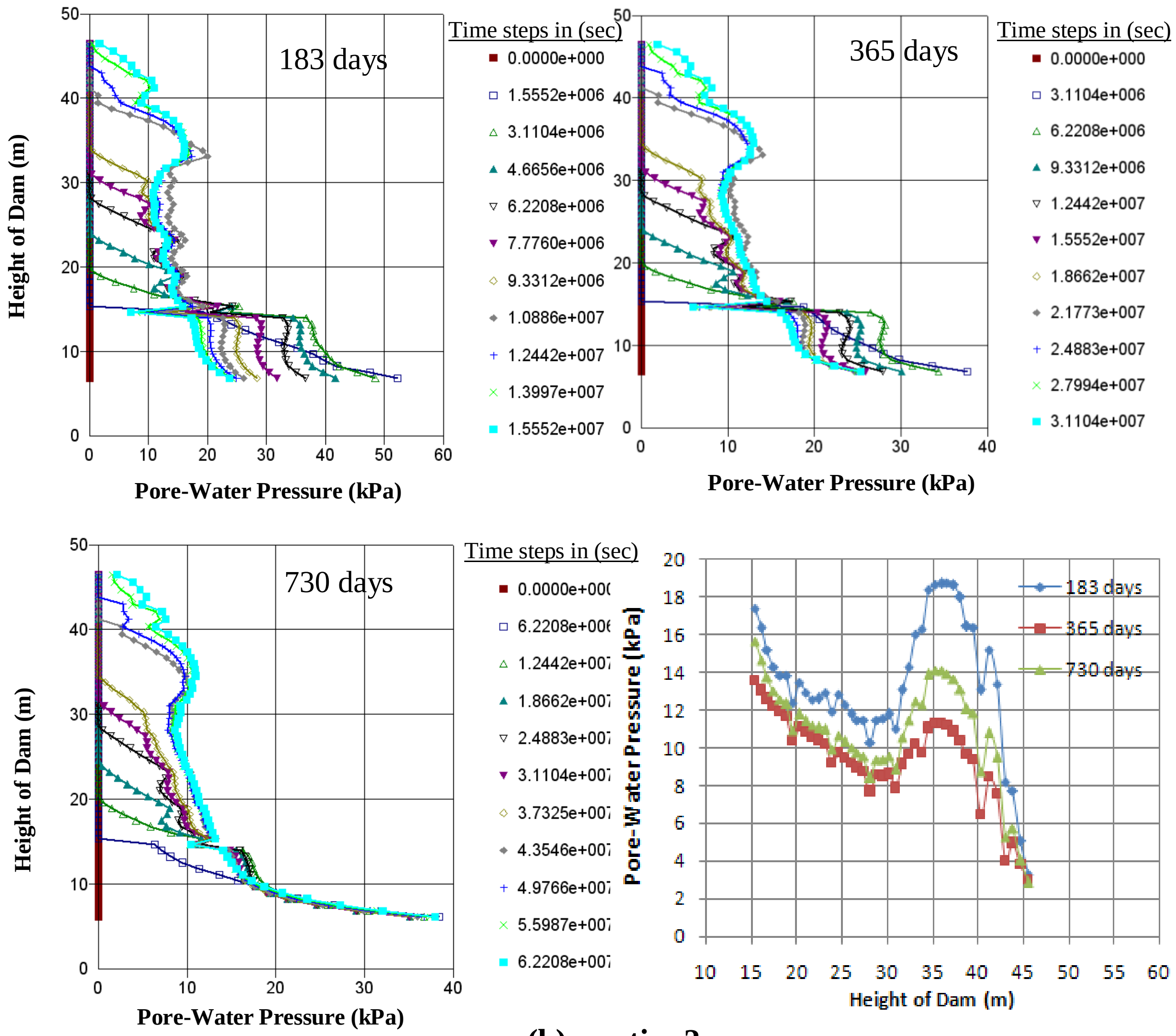
Pore water pressure developments during construction stage for the three selected sections (section1, section2, section3) were studied. The number of selected layers were assumed to be (10) from the foundation level. Consequently, the thickness of each layer is (9.5, 5 and 3.5 m) for sections (section1, section2, section3) respectively. The mesh (0.5 m) thick was used.

Figure (9) shows the positive variation of pore water pressure development during different construction stages within the clay core for the sections (1, 2, 3) at three selected possible construction times (183, 365, and 730 days). It can be seen that the pore water pressure increases under additional load due to increasing the height of filling.

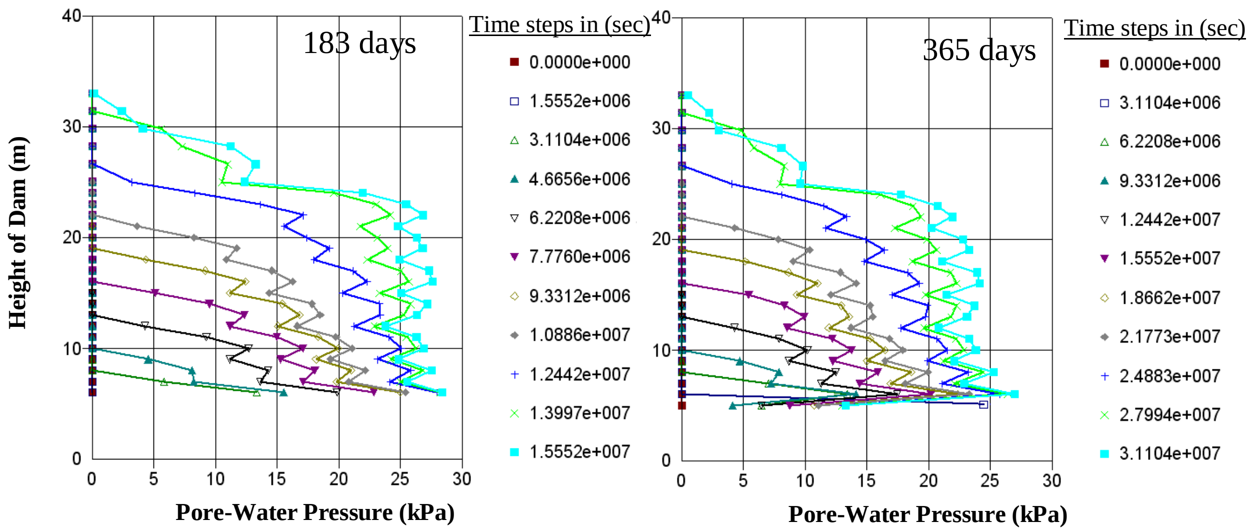
On the other hand, it could be seen from the stated figures that the construction time will affect the value of pore water pressure development, so the pore at the end of a construction time (730 days) was less than that at the construction times (365, and 183 days) for the three sections (1, 2, and 3). This could be attributed to the enough needed time to dissipate the pore water pressure than the two other selected construction times.

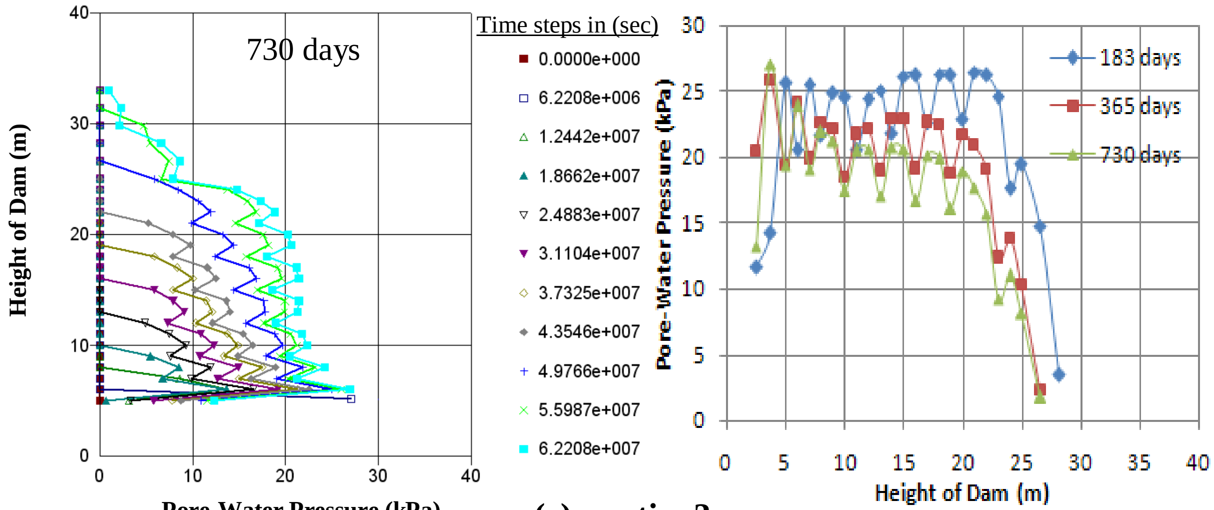


(a): section1


183 days
Height of Dam (m)
Pore-Water Pressure (kPa)
Time steps in (sec)
0.0000e+000
1.5552e+006
3.1104e+006
4.6656e+006
6.2208e+006
7.7760e+006
9.3312e+006
1.0886e+007
1.2442e+007
1.3997e+007
1.5552e+007
365 days
Pore-Water Pressure (kPa)
Time steps in (sec)
0.0000e+000
3.1104e+006
6.2208e+006
9.3312e+006
1.2442e+007
1.5552e+007
1.8662e+007
2.1773e+007
2.4883e+007
2.7994e+007
3.1104e+007
730 days
Height of Dam (m)
Pore-Water Pressure (kPa)
Time steps in (sec)
Pore-Water Pressure (kPa)
Height of Dam (m)
183 days
365 days
730 days

(b): section2

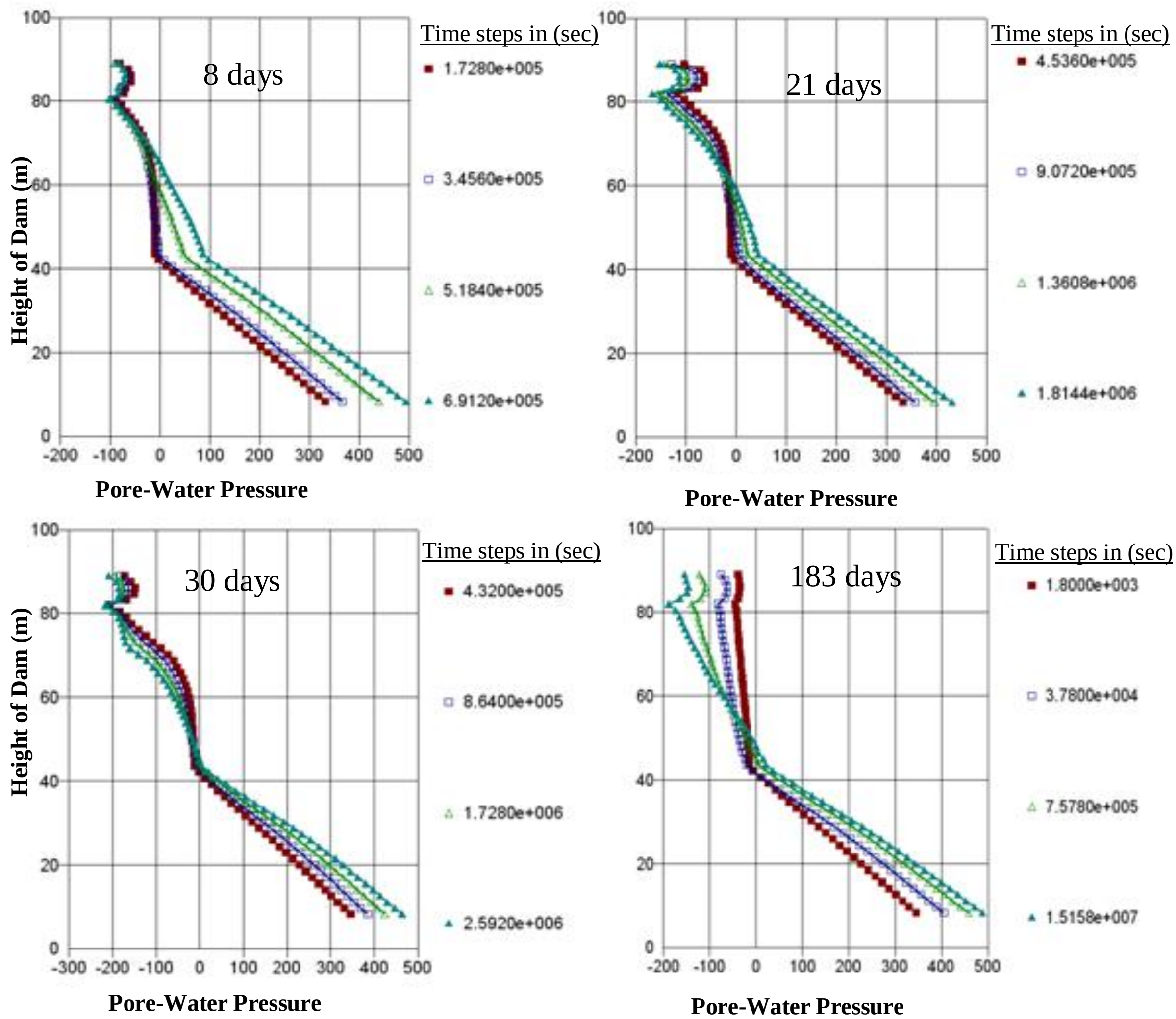

183 days
Height of Dam (m)
Pore-Water Pressure (kPa)
Time steps in (sec)
0.0000e+000
1.5552e+006
3.1104e+006
4.6656e+006
6.2208e+006
7.7760e+006
9.3312e+006
1.0886e+007
1.2442e+007
1.3997e+007
1.5552e+007
365 days
Pore-Water Pressure (kPa)
Time steps in (sec)
0.0000e+000
3.1104e+006
6.2208e+006
9.3312e+006
1.2442e+007
1.5552e+007
1.8662e+007
2.1773e+007
2.4883e+007
2.7994e+007
3.1104e+007



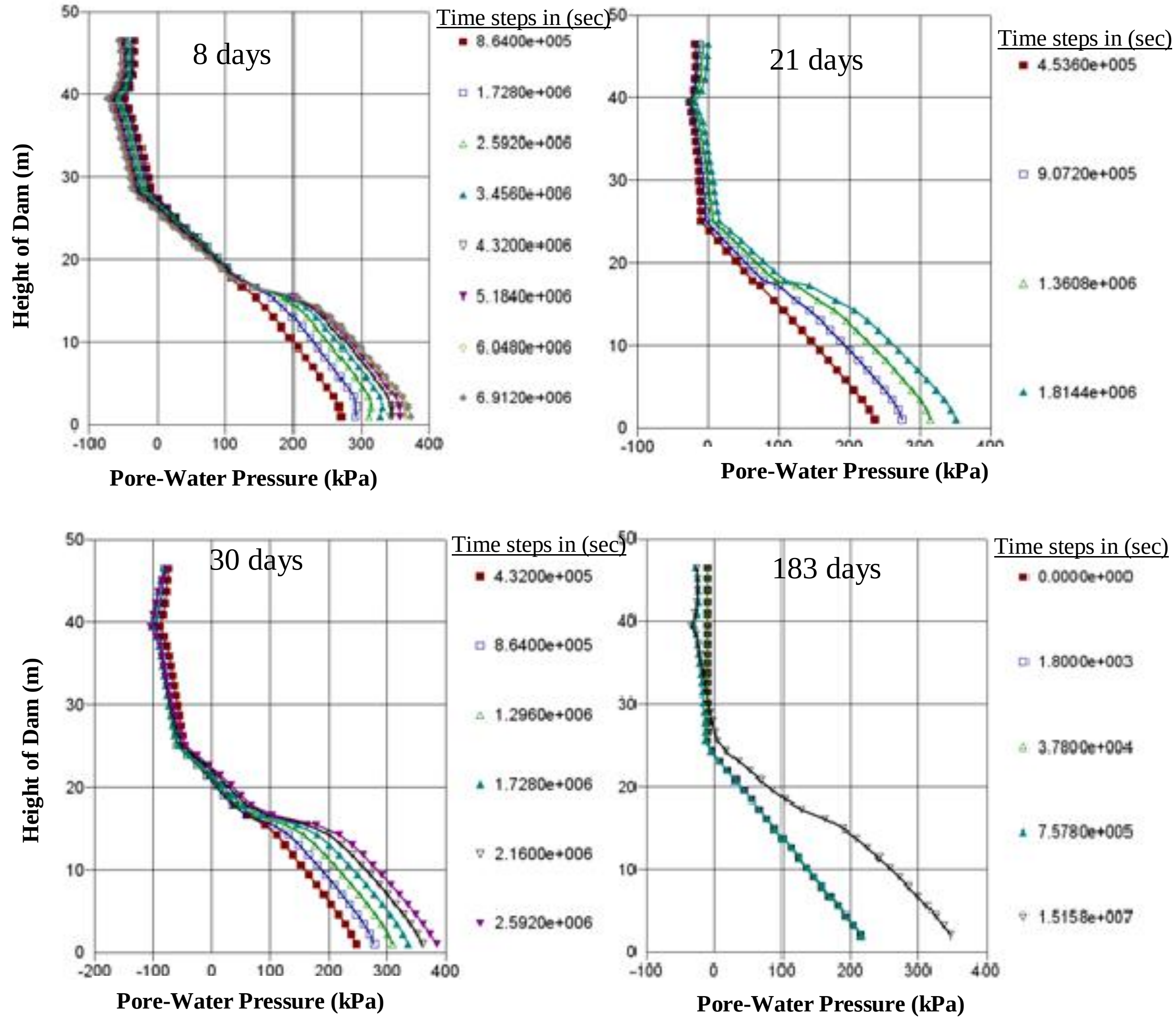
(c): section3

Figure (9): Pore pressure development during different construction stages

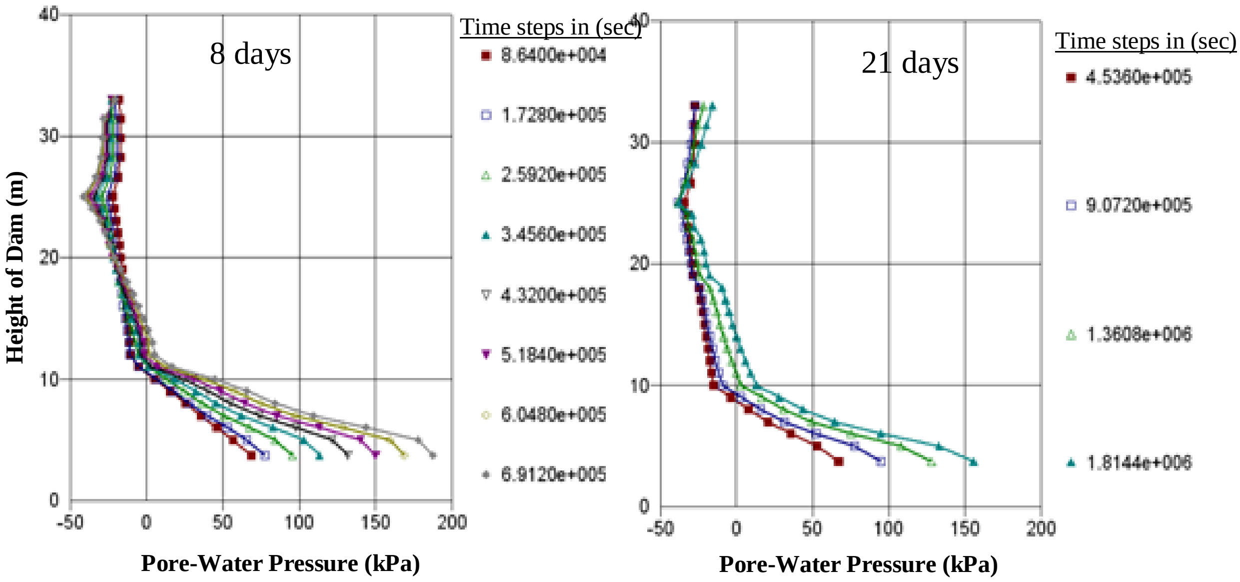
Figure (9) also shows that the height of earth dam will affect the pore water pressure magnitude. It can be noted that the high value of pore water pressure developed at the base of section1 (height 95m) then section2 (height 50m) and finally section3 (height 35m). It can be concluded that pore water pressure increases as a function of the filling height.

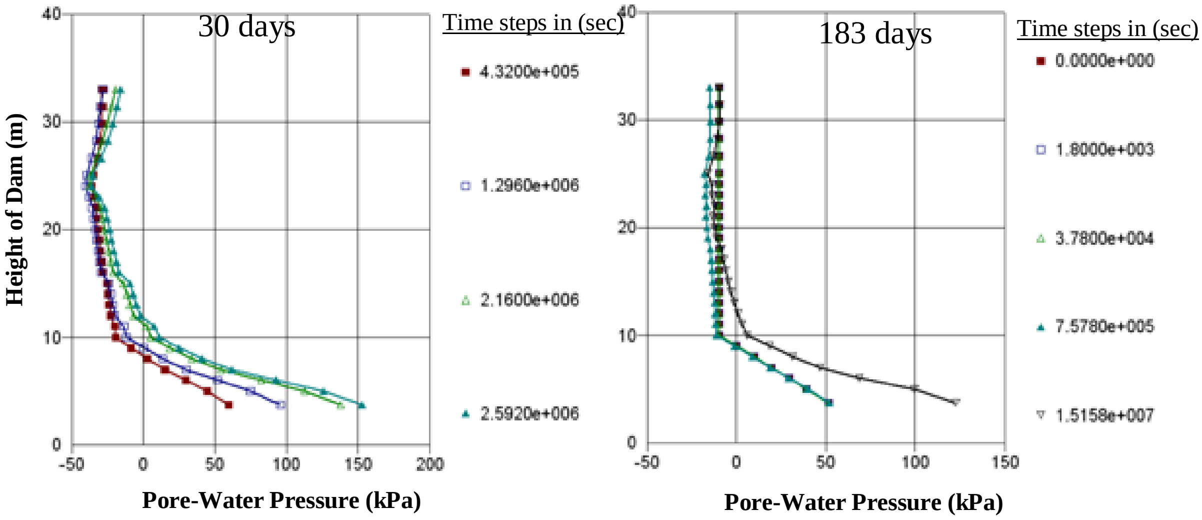


(a): section1


8 days
Time steps in (sec)
8.6400e+005
1.7280e+006
2.5920e+006
3.4560e+006
4.3200e+006
5.1840e+006
6.0480e+006
6.9120e+006
Height of Dam (m)
Pore-Water Pressure (kPa)
21 days
Time steps in (sec)
4.5360e+005
9.0720e+005
1.3608e+006
1.8144e+006
Pore-Water Pressure (kPa)
30 days
Time steps in (sec)
4.3200e+005
8.6400e+005
1.2960e+006
1.7280e+006
2.1600e+006
2.5920e+006
Height of Dam (m)
Pore-Water Pressure (kPa)
183 days
Time steps in (sec)
0.0000e+000
1.8000e+003
3.7800e+004
7.5780e+005
1.5158e+007
Pore-Water Pressure (kPa)

(b): section2


8 days
Time steps in (sec)
8.6400e+004
1.7280e+005
2.5920e+005
3.4560e+005
4.3200e+005
5.1840e+005
6.0480e+005
6.9120e+005
Height of Dam (m)
Pore-Water Pressure (kPa)
21 days
Time steps in (sec)
4.5360e+005
9.0720e+005
1.3608e+006
1.8144e+006
Pore-Water Pressure (kPa)



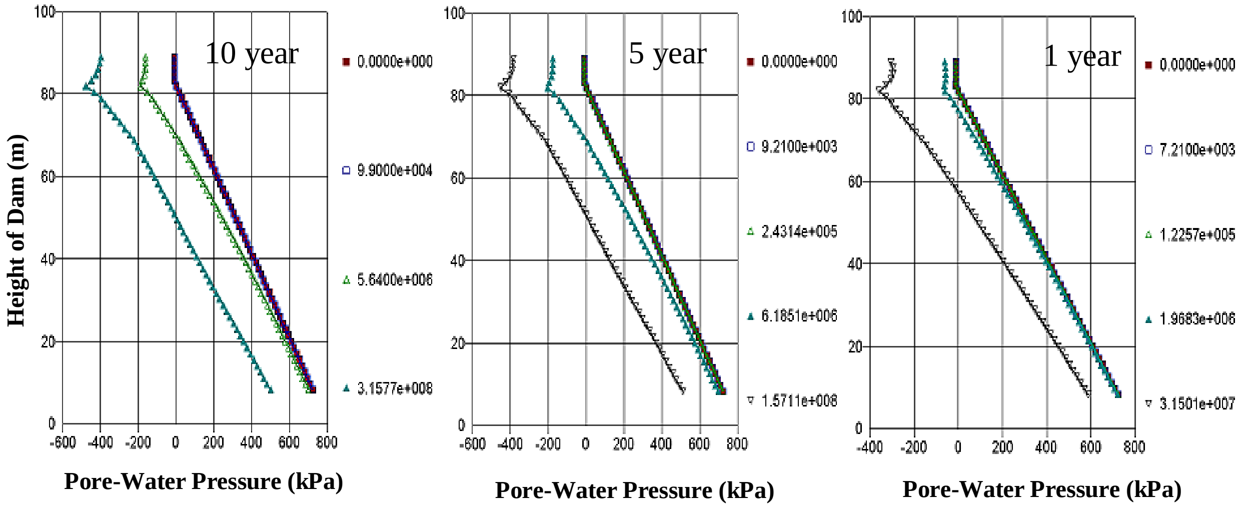
(c): section3

Figure (10): Pore pressure development during rapid rise water level

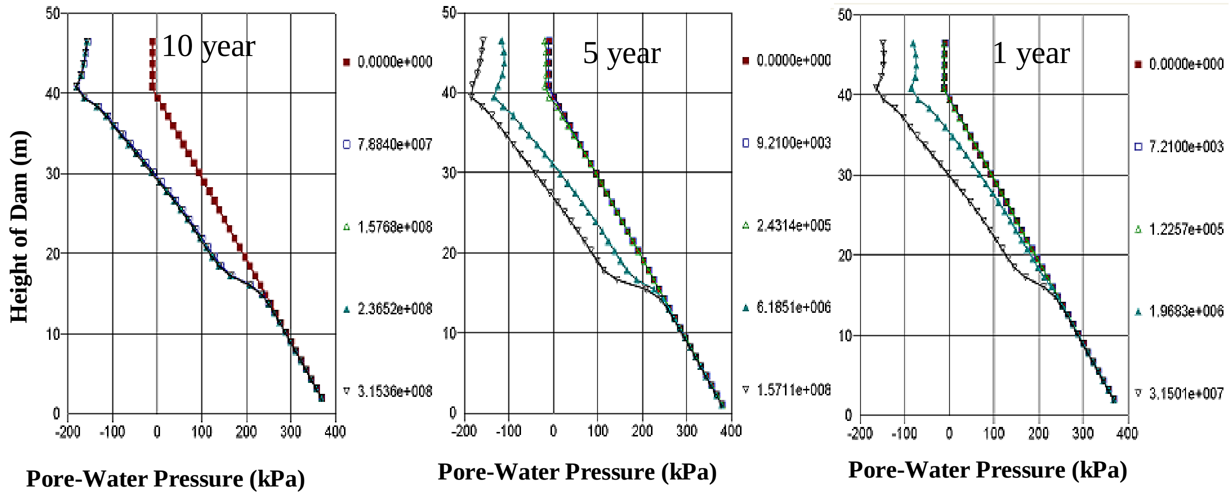
The pore water pressure distributions during saturated/unsaturated seepage flow through clay core, for BADUSH dam, during rapid rise in water level at periods of (8, 21, 30, 183 days) was shown in Figure (10). Pore water pressure distribution in the core was found to be positive within the lowest half of core while it becomes negative in the upper part near the highest level of core during rapid rise of water level at (8, 21, 30, and 183 days). More values of pore water pressures developing were recorded through section1.

Figures (11) and (12) presented the pore water pressure distribution in the core for the three selected sections (section1, section2, section3) at durations of (1, 5, and 10 years) when the water level are at maximum and minimum levels. The results are presented as positive pore water pressure development in the lower part of the core and negative pressures within the upper part of core. High pore water pressure was record through section1 rather than sections 2 & 3, this can be referred to the difference in the height of the earth dam embankment.

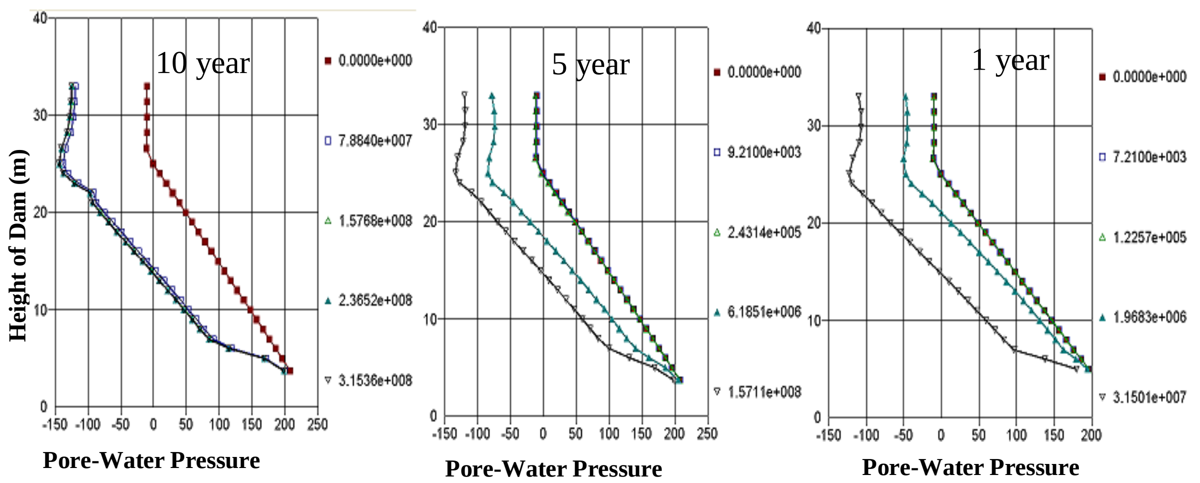
However, Figures (11),(12) show that the pore water pressure reached a steady state at the end of all periods of (1, 5, and 10) years for all the selected sections except section1 at a one year duration. A similar pore water pressure condition was obtained when the water level is at the lowest level. The obtained result from pore water pressure reaching to the steady state condition at three studied periods of (1, 5, and 10) years for selected sections (1, 2, 3). In general the behavior of the pore water pressure of this case (water level at lowest level) is similar to that in the case (of water level at highest level).



(a): section1

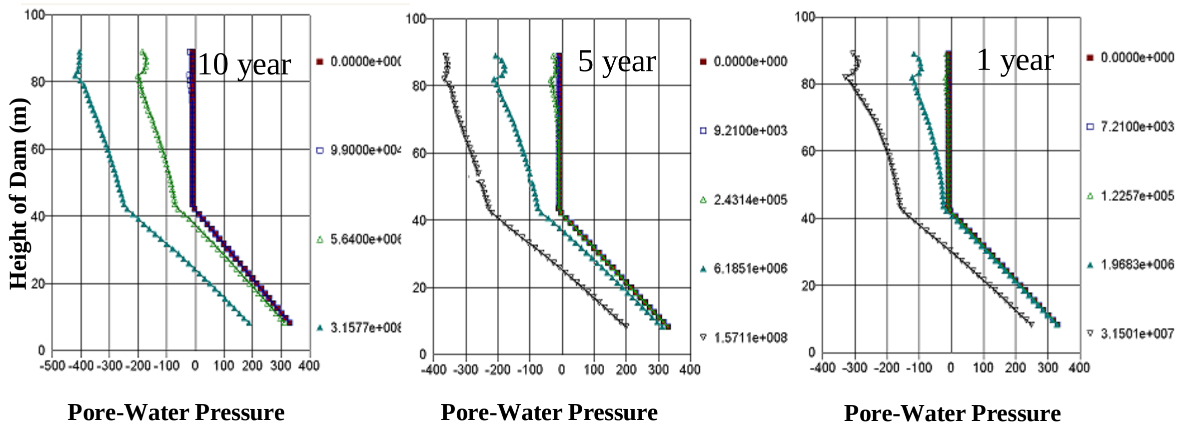


(b): section2

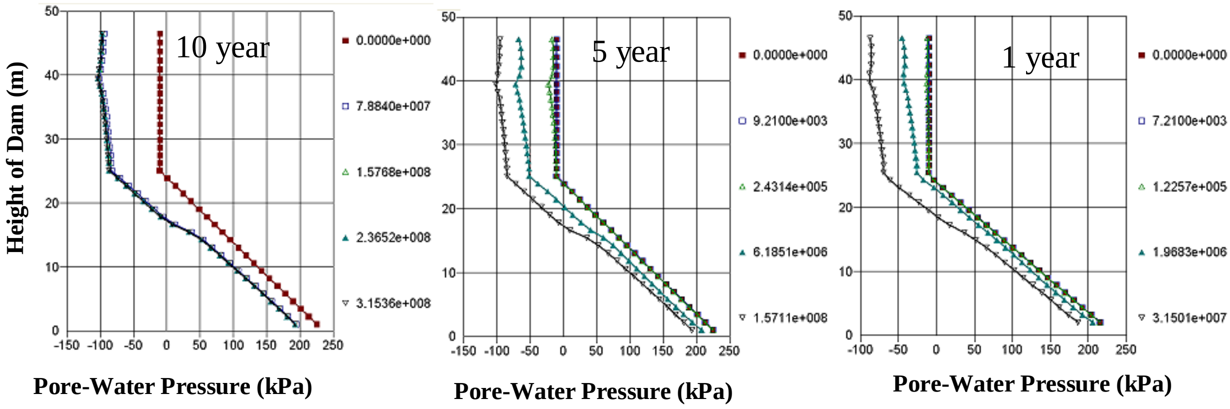


(c): section3

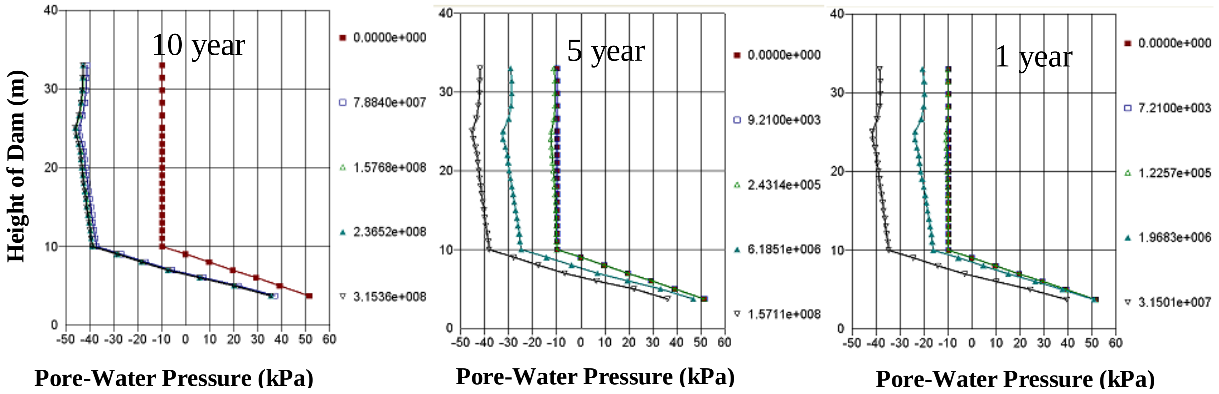
Figure (11): Pore pressure development at maximum water level



(a): section1



(b): section2



(c): section3

Figure (12): Pore pressure development at minimum water level

Two dimensional dynamic analysis of the possible pore water pressure development in the core of BADUSH dam during earthquake shaking was performed. This analysis was conducted at the end of time of rising water level (8, 21, 30) days.

The pore water pressure development is summarized in Figure (13) It could be showed that the possibility of the pore water pressure development recorded a high value if it is compared with the values at a normal stages, shown in Figure (10) .

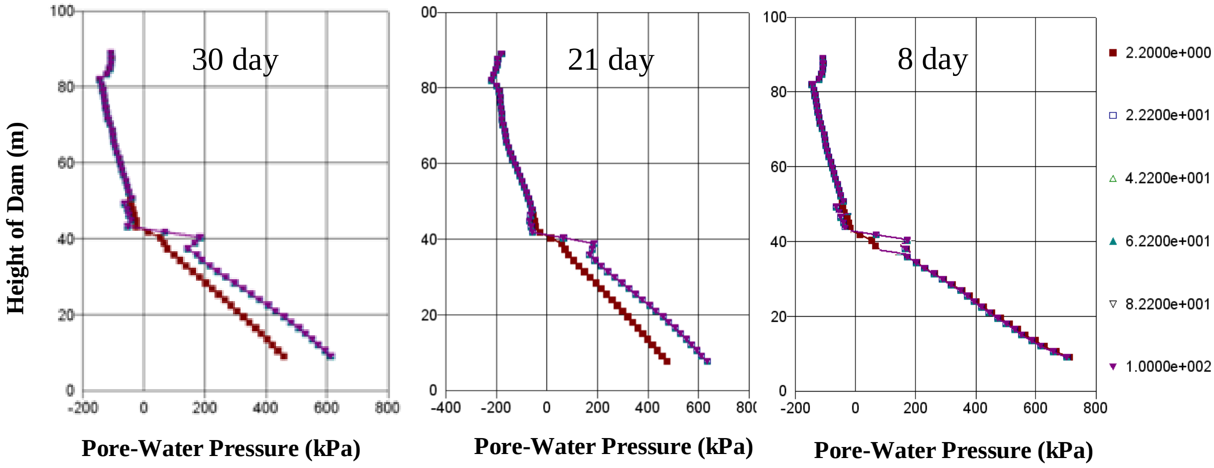


Figure (13): Pore pressure development during earthquake tremor at the end of time 30, 21, 8 days rising

Conclusions

Based on the preceding stated analysis the following could be concluded:

1. In the parametric study for the simulation of pore water pressure, the presence of a chimney drain is effective in reducing pore water pressure development. On the other hand, considering the saturated/unsaturated conditions, an increase in the negative pore water pressure values and a decrease in the positive pore water pressure were recorded when considering unsaturated condition in the analysis.
2. In the case study of BADUSH dam, the analysis showed that the height and construction time have an influence on the pore water pressure development during construction. A pore water pressure in the range of (175 kPa to 140 kPa through section 1) and approximately between (25 to 50 kPa) for the two other sections 2 and 3 at a periods of (370, 365, and 183 days) were recorded. It is worth noting also that the maximum pore water pressure is often developed within the lower part of the core with negative pore water pressure near the crest.
3. In the case of rapid rise of water level at 8 days, a positive pore water pressure was generated between (500 to 350 kPa) through the sections 1,2 and 3.
4. Finite element method gives a good understanding of pore water pressure development within the core of a dam during possible earthquake loading. About twice the value of positive pore water pressure was obtained as a result of a virtual proposed earth quake comparing with the normal studied case.

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