Numerical Analysis and Monitoring of an Embankment Dam During Construction and First Impounding (Case Study: Siah Sang Dam)

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ABSTRACT

Monitoring embankment dams is of crucial importance. In earth dams, the pore pressures, earth pressures, and displacements occurring during construction and function, are measured at the time of the first impounding and exploitation by installing essential instruments and so the dam's performance is evaluated and analyzed. Scope of the present research is the evaluation of the performance of Siah-Sang dam through using the results of instruments and back analysis which has been conducted by FLAC software.

The Mohr-Coulomb elastic-plastic model has been considered as the behavioral model of the dam and the effect of the upstream shell's materials deformation has been modeled at the time of the initial impounding. Following that, comparing the results of the numerical analysis with the measured values, indicates that there is a proper consistency between these two values. Moreover, it was observed that the dam's performance was suitable regarding the created pore water pressure, displacements and stresses in the construction period as well as during the first impounding. In addition, susceptibility of the hydraulic fracturing was assessed by calculating the arching ratio and it was concluded that this dam is secure in comparison with the behavior of other similar dams in Iran and the world.

Key words: Earth dams, Initial impounding, Numerical Modeling, Instrumentation, Vertical displacement, Stress

1. Introduction

Geotechnical structure designers are concerned with different kinds of anisotropic and heterogeneous materials which have complex and unstable behavior and geometric characters. Designers select these element and behavior parameters because they are important in planning and analysis of steps. Monitoring is very important because determination of exact stone, soil and earth dam characters are very difficult. The behavior evaluation is achieved by installation a device called instrument. Monitoring and instrumentation is considering of structure action during building and utilization and adoption with predicted time. Different factors like liquefaction, pitched roof slippage, piping affection complexity of soil behavior we need to install determining device in important and critical places to consider and evaluate soil forces and structure deformations. This device is called instrument in technical literature to observe the actual behavior to prevent the failure caused by different factors, so dam continuous monitoring is necessary. We use exact device, to read data in different periods, to evaluate data behavior. A back analysis is used to determine and reject instability factors.

Duncan [1] and Kovacevic [2] are recent main references on the state of the art in finite element analyses applicable to the deformation behavior of embankments, mainly zoned earth and rockfill dams. They discuss the methods of analysis, their limitations, available constitutive models of the stress-strain relationship and areas of uncertainty. As Duncan points out, most analyses from the literature are Class C1according to Lambe [3], i.e. after the event, which may account for the generally good agreement between predicted and observed deformation behavior.

An important component of the modelling of embankment dams is the consideration of collapse Vertical displacement of susceptible rockfills and earthfills on wetting. The effects of collapse Vertical displacement are most noted for the upstream shoulder on initial impoundment, but collapse Vertical displacement has also been observed in the downstream shoulder following wetting due to rainfall, leakage or tail-water impoundment. Incorporating collapse Vertical displacement into constitutive models adds further complexity and greater uncertainty in the estimation of material parameters between laboratory and field conditions due to the dependency of collapse Vertical displacement on compaction moisture content, compacted density, applied stress conditions and material properties. Justo [4] and Naylor [5] propose methods for incorporation of collapse Vertical displacement of rockfill into constitutive models. The analysis of Beliche Dam, a central core earth and rockfill dam, by Naylor [6] is an example where collapse Vertical displacement of the upstream rockfill was considered in the modelling.

The effect of pore water pressure dissipation in earthfills during construction also has been considered by a number of authors including Eisenstein and Law [7], in modelling Mica dam, and by Cavounidis and Höeg [8],amongst others. For these cases, the incremental embankment construction was modeled as a two stage process, the first stage modelling the new layer construction using undrained properties for the core and the second stage modelling pore water pressure dissipation. In most cases though, pore water pressure development in the core is ignored. For wet placed earthfills, where high pore water pressures are developed during construction, the core is often modelled using undrained strength and compressibility parameters, and the permeability is assumed as sufficiently low such that pore water pressures will not dissipate during the period of construction. In addition, David Zumret al [9] investigated the solution based on transient simulation of seepage on earth dam through protection. Simulations were carried out by a two-dimensional numerical model based on Richards' equation for water flow in porous medium. It has been shown that proposed approach is suitable for large scale engineering applications.

This paper first introduces the Siah Sang dam, Kurdistan, Iran, and reviews results of monitoring of the instruments installed in the dam. Then it introduces numerical back-analyses of the dam for the end of construction and first impounding loading. Finally, it presents the results of the analyses and compares them with the monitoring results.

2. Siah Sang Rock-Fill Dam

2.1. General Characteristics

Siah Sang dam is 33 meters high, the length of the crest is 352 meters and the volume of the container is approximately 255,000square meters. The dam is an earth dam with a clay core and is located in Kurdistan province in Iran. To make a graph of the dam's behavior, accurate instruments were chosen in 3sections which included piezometers, total soil mass pressure measurement cells, Vertical displacement meters and inclinometers which were installed within them. Taking into account the foundation type, the height of the earth-filling and the depth of the valley, the most critical cross section of Siah Sang dam regarding the accumulation of pore water, maximum Vertical displacement and tolerance, is the profile located in 0+175 kilometers which. The evaluation and numerical analysis would be done in this profile in this study. Also the material properties used in the numerical analysis were extracted from certain soil mechanical laboratory tests on the fine and coarse materials of the dam. Table 1 shows the parameters of Mohr- Coulomb elastic- plastic model for various zone of the dam [10].

3. Instrumentation Results

In earth dams, with the premise that other conditions are similar in all points the most critical section regarding stability is always the highest section. Also most of the stresses, displacements and pore water pressures usually take place in this section. Since as seen in Figure 1there are three sections in Siah Sang Dam in which they have set up instruments and it is not possible to analyze all these sections within the limited duration of the present research, the researcher will only the stress-strain behavior in critical sections is presented. Clearly if the behavior of the dam in critical sections is understood accurately, this behavior could be generalized to all sections of the dam.

3.1. Evaluations of Instrumentation Results and Dam Behavior

3.1.1. Vertical displacement

To measure displacement of the dam in profile B according to figure 2, two tubes of inclinometers are installed in the downstream and upstream of the dam. The initial position of the casing is established in a survey taken with the inclinometer probe. Ground movement causes the casing to move from its initial position. The rate, depth, and magnitude of this displacement is calculated by comparing data from the initial survey to data from subsequent surveys. In figure 3Vertical displacement amounts of the core in accordance with the dam's height is observable from the time the dam was constructed in six different time intervals. According to the graph December 2006 is the date when the construction of the dam came to an end, the maximum Vertical displacement in the last reading on this date is equal to 18 centimeters. The initial impounding of Siah Sang dam had begun also form January of 2007 and then Vertical displacement in the June of 2007 was 20 centimeters. It is observed that from the initial impounding to the dam exploitation which took approximately 6 months, the Vertical displacement was only 2 centimeters. This Vertical displacement is 10% of the total Vertical displacement of the dam. While 90% of the

Vertical displacements was 18 centimeters and they took place in the construction time as it is seen in the graph in some points in time. Also, in figure 4 the Vertical displacement amounts are presented from the Vertical displacement meter tubes in downstream with accordance to level and in seven intervals. On date when the hard operation of earth-filling was finished, (December 2006) the maximum of its Vertical displacement, is 21 centimeters which is located in the 15 meters of the height of the body of the dam, whereas this amount during impounding was just 1 centimeter.

Figure 5 compares Vertical displacement amounts at the end of construction operation (December 2005) in 2inclinometer tubes. As it could be seen the difference between core Vertical displacement of upstream and downstream is not significant and the difference is due to the difference between behavioral characteristics and compressibility of the materials of the core, filter, drainage and shell. Considering the materials of the upstream, the downstream and the central core are similar, the difference between the Vertical displacements in the upper part of the dam is very little. It also shows Vertical displacement amounts 6 months after the beginning of the initial impounding (June 2007). The important point is the increase of the upstream shell Vertical displacement in comparison to the downstream the reason for this is the hydrostatic pressure of water on the upstream shell and causes more Vertical displacement.

3.1.2. Vertical Stress

Total pressure cells have been installed in three levels as seen in figure 6 in 1810.5, 1817.5 and 1825 level the calls have been installed in a bunch of 3, 5 and 1respectively.Figure 7 shows the changes in total vertical stress in the pressure cells installed in 1810.5 level in accordance with earth-filling. Vertical stress changes process is steady and in tune with the progress of dam construction and the fill height.

In figure 8there are the changes in the vertical stress in the width of the core and upstream and downstream filters in the first level at different points in time. As it can be seen with the increase in the levels of earth-filling, the stress level in all the width of the core and the filter also increases. The maximum read stress most of the times is related to number TPC2-1pressure cell which is located within 8 meters upstream of the dam axis inside clay. Which at the end of the construction operation its amount was 325 kilopascals.

3.1.3. Arching ratio

Shell materials including rockfill and gravel were stiffer than the materials used in the core. Difference of elasticity modulus between these two kinds of materials made various tendencies to Vertical displacement. In addition, the friction between the core and shell materials caused a transfer of stress from the core to the shell, which could create a low-stress area in the core; this phenomenon is called Arching in earth dams. Equation 1 presents the arching ratio:

$$A_r = \frac{\sigma_v}{\gamma.h} \qquad (1)$$

Where σ_v: is vertical total stress (kPa) γ: is unit weight (kN/m^3) and h: is embankment height (m) [11, 12].
Since core is softer than shell, load transfer occurs from core to shell. As a result of this action, pore water pressure can become more than total stress within core. This action may make of cracks due to excessive water pressure. These cracks are called hydraulic fracturing that makes holes from upstream to downstream. Also, it makes a serious damage to the body of the dam, possibly leading to the dam failure. The higher the A_r , the less the arching phenomenon in the core and the lower the probability of hydraulic fracturing would be.

In figure 9 the changes in the ratio of vertical stress to the load or to put it another way the arching ratio in the width of the core and the filters in the first level (+1811.5) in the 21 and 26metersfill height are shown towards the end of construction operation. As it could be seen the most critical of the arching ratio in 21meters fill height was about 0.7. This issue indicates the fact that only 69 percent of the load weight on the core in this fill level is transferred to the materials underneath it and 31 percent of the rest if the weight transferred to the shell and side filters of the core. It is seen 26meters fill height of Siah Sang dam the most critical of the arching decreases 0.67 with the difference that the arching ratio in the upstream areas increase and it even reaches 0.72 but in the downstream areas this amount was just under 0.69. Comparing ratios obtained with arching ratios of Iran‘s largest dams like: Molla Sadra earth dam with 72 meters height that its critical arching ratio is 0.45 and Gavoshan earth dam with 125 meters height that its critical arching ratio is 0.52 and considering that the more the arching ratio is ,the less the created arching will be, we reach this conclusion that Siah Sang dam will have no problem regarding hydraulic fracturing[13,14]. Also, it should be noted that the bulk density of the core material providing arching ratio in different fill height was 17.4kN/m3.

4. Numerical Analysis

Siah Sang Dam is modeled in 15 layers. The height of the earth-filling layers with regard to the execution time, are defined to be between 1.5 to 2 meters. First the cofferdam was modeled with regard to the time it was constructed and then the layers were modeled. After constructing each layer and analyzing it its displacements on the layer became zero. You should pay attention that the thickness of every layer should be one element if not the patterns of the changes in the vertical shapes of the body of the dam in the numerical model will be as disorganized curves. The Siah Sang dam impounding was done in 3 layers similar to its construction, the height of the layers are between 7 to 9 meters. Each layer's impounding was carried out considering the height code of the water behind the dam which was obtained by instruments. The first total impounding of the dam was done in 6 months. It should be noted that in the numerical analysis the rocky foundation was not modeled which the main reason was the little settlement of it during construction (0.5 centimeters), low permeability which was approximately 1×10^{-6}m/s and also because of the concrete slab which is in the bottom of the clay core and its thickness which reaches 50 centimeters which added to the reasons why modeling the foundation was avoided to accelerate analysis.
As in figures 10 to 14 the results of the analysis are presented in 2 phases of the impounding of the dam these phases include from the 27 meters of the fill before the beginning of the first impounding and in the end of first impounding.
The numerical analysis was done using FLAC software [15] and Mohr-Coulomb elasto-plastic model was used for the rockfill, filters and earthfill core. The limitations of using such a simplistic model are recognized, but the main purpose of the analysis was to evaluate the stress conditions within the embankment to then use the stresses in the analysis and interpretation of the monitored deformation records. Also for the first impounding analysis the Justo method was used separately in unloading the lower layers due to submerging [4]. Because of the effect of impounding the inner friction decrease angle coefficient of the material were imagined to be 20% regarding technical literature [16][17]. Young's modulus decrease coefficient was also imagined to be 50% with regard to the carried out studies [18][19].
The steady state seepage calculation is performed after the completion of the staged construction. Steady state seepage of the dam for a 25 m water level is then performed without interaction with mechanical equilibrium. The final state of static equilibrium, called initial stress state, of the dam was then computed again after the steady state seepage has reached.

4.1. Examining the degree of accuracy of the number of elements in the results of numerical analysis

The degree of the accuracy of the number of elements has been analyzed many times since regression analysis operations have been carried out in the numerical analyses and numerical computations were required. Two types of models were generated for that. The properties of the materials and their geometric shape are in accordance with Siah Sang dam. The first sample which could be seen in figure 15, it has coarse mesh size and 750 elements, the number of its layers are equal to the number of the elements in the vertical direction in the numerical computation in time of construction which means its vertical displacements will be equal to zero after every layer is constructed. And like the real construction time, the vertical displacement of all the elements will be zero once.
The second sample has fine mesh size and 7500 elements. The time the program needs to run is very long for the second sample. The number of its layers are 15 at the time of construction, like the first sample. The difference between them however is that each layer has a number of rows of vertical elements on top of each other and after each layer is run, only the top element's vertical displacement will be equal to zero this will lead to the vertical displacement or the dam Vertical displacement results being disorderly and fluctuated. Figure 16 has shown the difference between Vertical displacement in the first and the second samples.

In addition, Examining the degree of accuracy of the number of elements in the results of the numerical analysis made it clear that making the elements coarse and decreasing their number from 7500 elements to 750 elements will increase the ratio of the total vertical stress and pore water pressure values 2 and 3 percent respectively and decreases vertical displacement 4 percent, nevertheless it was used the first sample or coarse mesh in order to accelerate the computations and also to better show the changes in the vertical displacements.

4.2. Comparing the Instrumentation Results and the Numerical Results

The evaluation will be completed in case a back analysis is carried out in order to control the degree of the accuracy and the level of confidence of the measured behavior since each of the measurements could be controlled through comparing it to the model obtained from the numerical model. This process and solution algorithm has been described in figure 17.

4.2.1 Vertical displacement results

The internal Vertical displacements of the dam are categorized into three groups: vertical, horizontal, and rotational movements. Vertical movements show the Vertical displacements in terms of material weight, compaction, and consolidation of the dam body. Horizontal movements mainly refer to the upstream movements that occur during impounding in the dam storage, which is due to faster reduction of the effective stress in the upstream materials than in other parts of the dam. Downstream movement is due to the horizontal water pressure of the dam storage. Furthermore, rotational movements that appear in the upstream and downstream slopes are because of lower shear strength of materials in the foundation or body of the dam. Using surveying points, inclinometers (Vertical displacement tubes), and/or Vertical displacement gauges is a conventional way for measuring these deformations in earth dams. In this study, an evaluation was only made of the results of the vertical displacements in the Siah Sang dam obtained from inclinometers, because the readings related to horizontal displacements were not available due to poor archive in the early years of the dam construction by the consulting engineers of the project.

In figure 18 the Vertical displacement of the upstream height of the central core is compared considering the results obtained from instruments and the amounts from numerical modeling respectively in December 2006 (towards the end of the construction operation) and June 2007 (after the initial impounding). As it is observed the analysis results are very close to reality in both times. Additionally, it compares the downstream shell's Vertical displacement obtained from instruments and the amounts obtained from numerical modeling in the two mentioned times in the last section. At the end of construction operation these results are close to each other, also after the initial impounding the results in the lower part of the dam are convergent. In addition, the reason of undulation of the measured maximum Vertical displacements from instruments would be differences in soil compaction and Soil heterogeneity in different layers of dam, while they should be theoretically smooth.
The inclinometers' reading are compared with numerical models in relation to the Vertical displacement changes in different levels of the dam with accordance to the time in figure 19. As it is observed, tangible differences between them was only in lower layer (10m) in relation to upper layer (19m) which was close to each other. It also shows the Vertical displacements of the dam was decreased significantly after 400 days (at the end of construction and the start of initial impounding).

4.2.2. Vertical Stress results

In figure 20 the process of the appearance of the vertical stress in the piezometers located in the first level has been displayed in accordance to time. As it is observed the analysis results are very close to reality except differences between vertical stress in numerical model with reality taken place after construction in TPC2-1. This amounts were close to each other before initial impounding, while it diverged during initial impounding. It was expected that vertical stress increased with the same as the result of numerical analysis, but due to broken piezometer, this amount remained steady in instruments' results. Furthermore, as demonstrated by the results in figure 20, there was a difference between the observed and calculated vertical stresses in TPC2-2, the vertical stresses in the pressure cells were lower than those obtained by the numerical analysis. There were some reasons as why results were divergent after the initial impounding (after 400 days) in upstream of the central core. Calibration of the instruments for load and temperature is a difficult and expensive task so that lack of calibration and destruction of instruments is assumed possible [20]. In addition, to prevent damage to the pressure cells, the soil around the cells was compacted in a lower density in comparison to other parts of the core. Consequently, the reality of the soil stiffness in the body of the dam was mostly more than that around the cells.

5. Summary and Conclusion

The purpose of this study was to make an effort to present a general evaluation of the function of the dam during construction and the initial impounding through the data obtained from instruments from Siah Sang earth dam and also utilizing modeling and carrying out numerical analysis regarding the stress-strain behavior of the dam. The result gained from this study are as follows:

- According to the numerical analysis, the Vertical displacement results were consistent with the data recorded by the instruments in terms of both quality and quantity, showing that the maximum Vertical displacement of the core was 18 centimeters at the end of construction. In the following 6 months after construction (initial impounding and exploitation period) the accumulative Vertical displacement of the dam was 20 centimeters. It is clear that 90% of the total Vertical displacement of the dam took place while dam construction and the reason is the clay core being smashed in the wet side, optimal moist. The aforementioned maximum Vertical displacement showed that this value was at the rate of about 0.7 % of the height of the dam.
- Total vertical stresses, extracted from the numerical analysis, proved to be in a tolerable trend with the data recorded at the pressure cells; but, there was a small difference from quantity. Inconsistency between the stresses obtained from the numerical analysis and pressure cells was mostly due to the local arching phenomena in the installation place of the pressure cells, which was due to inadequate compaction around these instruments that caused creating a low-stress zone.
- The arching ratios were calculated for the largest cross-section of Siah Sang dam. The results demonstrated that the arching ratio in Siah Sang dam was 0.67 to 0.76, which placed the dam on the safe side in terms of hydraulic fracturing. In addition, Examining the degree of accuracy of the number of elements in the results of the numerical analysis made it clear that making the elements coarse and decreasing their number from 7500 elements to 750 elements will increase the ratio of the total vertical stress and pore water pressure values 2 and 3 percent respectively and decreases vertical displacement 4 percent. Therefore, it is better to use the first sample or coarse mesh in order to accelerate the computations and also to better show the changes in the vertical displacements.

Finally, it is worth mentioning that the behavior of this dam in its largest cross-section was reasonable in terms of Vertical displacement and stresses at the end of construction and first impounding.

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Table1. Initial amounts of material parameters in the body of the dam

Elements parameters	Dry Unite Weight (kN/m^3)	Inner Friction Angle (degree)	Cohesion (kPa)	Elasticity Module (MPa)	Poisson Coefficient	Dilation angle (degree)	Permeability Coefficient (m/s)
Core	16	30	15	5000	0.4	0	1.16x10^{-9}
Upstream & Downstream shell	18	34	1	15000	0.35	13	9.26x10^{-8}
Filters & Transition	18	36	3.5	10000	0.3	7	2x10^{-4}

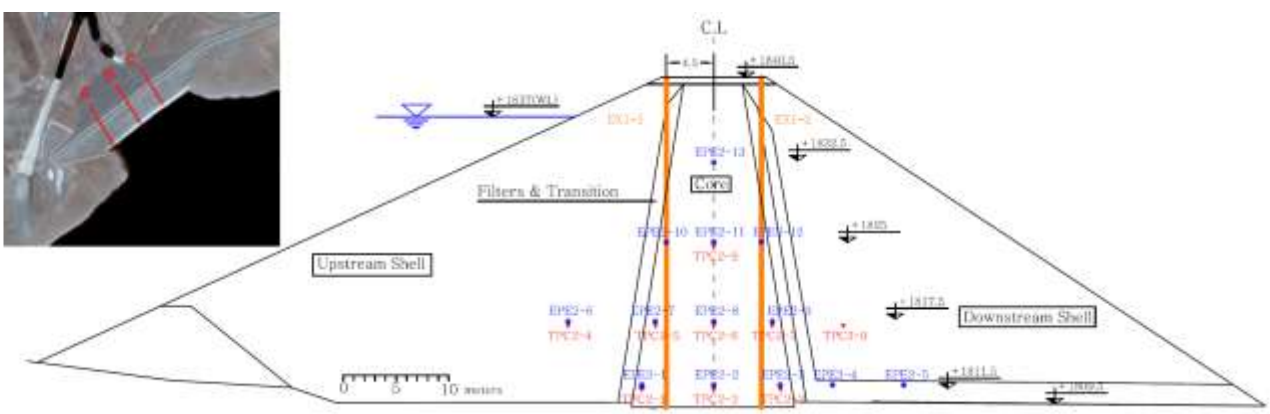


Figure 1. The plan view of Siah Sang dam and arrangement of instruments in Section B (Critical Section) [9]

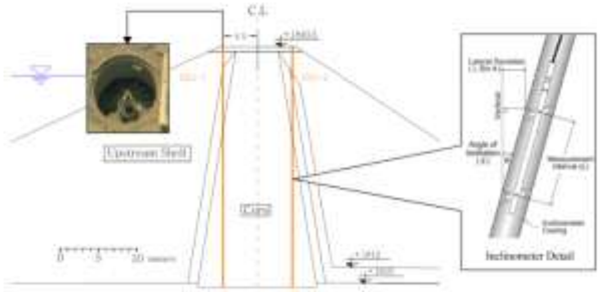


Figure2. The arrangement of Inclinometers and their details in Siah Sang dam [9]

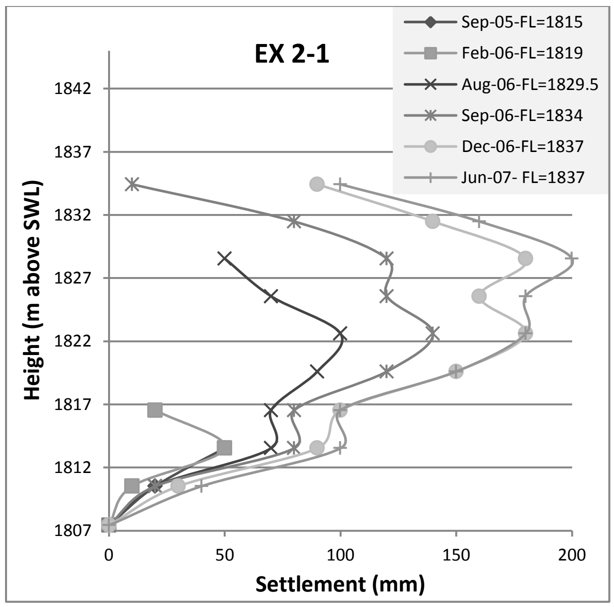


Figure3. Upstream central core Vertical displacement in accordance with dam's height in different times (measured values are depicted)

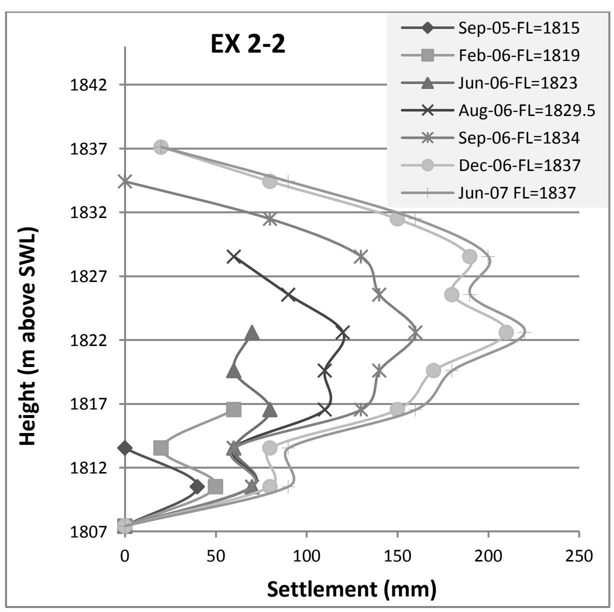


Figure4. Downstream central core Vertical displacement in accordance with height in different times (measured values are depicted)

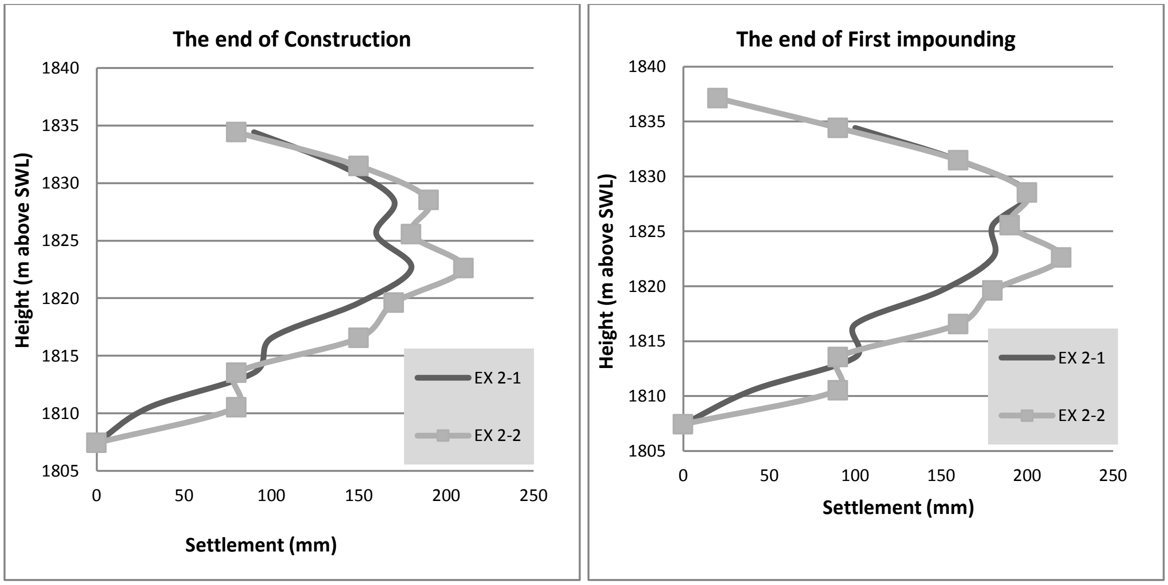


Figure5. Vertical displacement in different heights in central core upstream and downstream (measured values are depicted)

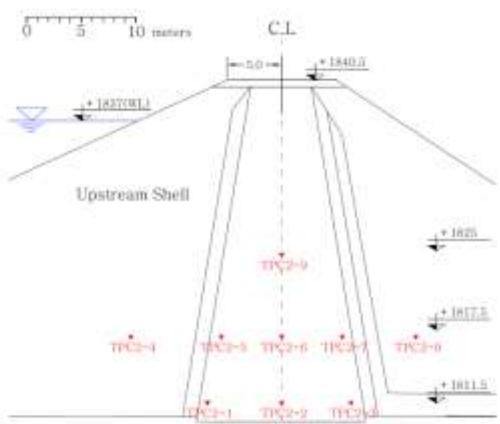


Figure6. Total pressure measurement cells in different levels [9]

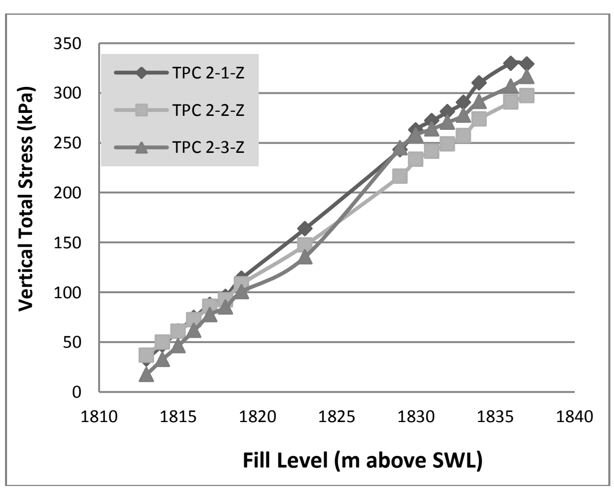


Figure7. Changes in total vertical stress in the pressure cells installed in the first level in accordance with time (measured values are depicted)

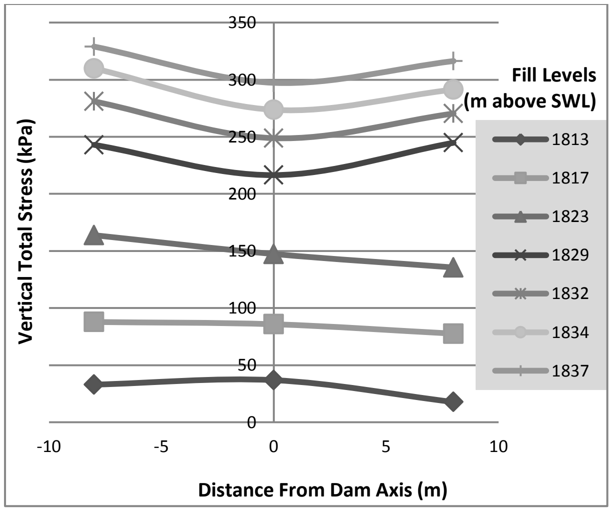


Figure8. Changes in total vertical stress in the width of the dam body in the first level in different fill levels (measured values are depicted)

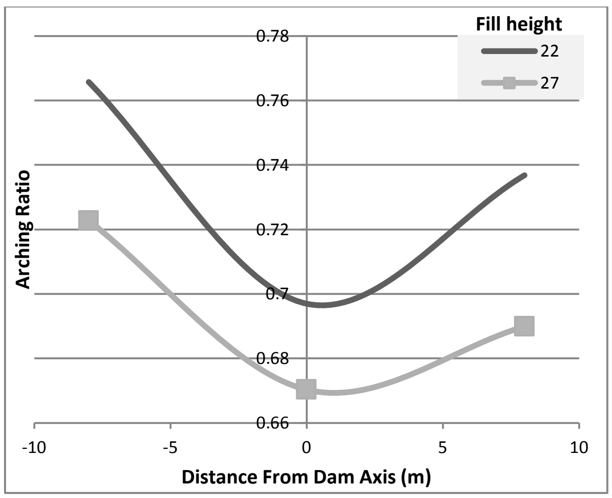


Figure9. Changes in arching ratio in the width of the dam body in the first level in different fill height (measured values are depicted)

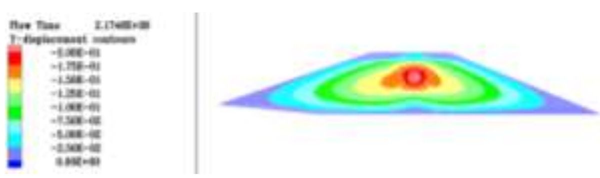


Figure10. Vertical displacement of the dam (before starting the initial impounding)

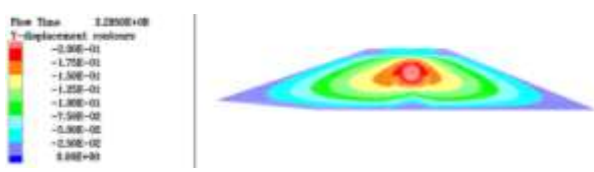


Figure11. Vertical displacement of the dam (in the end of first impounding)

Figure12. Pore water pressure of the dam (before starting the initial impounding)

Figue13. Pore water pressure of the dam (in the end of first impounding)

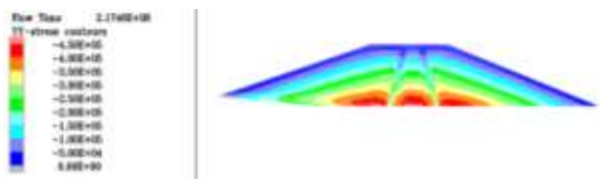


Figure14. Dam's vertical stress level curve (before starting the initial impounding)

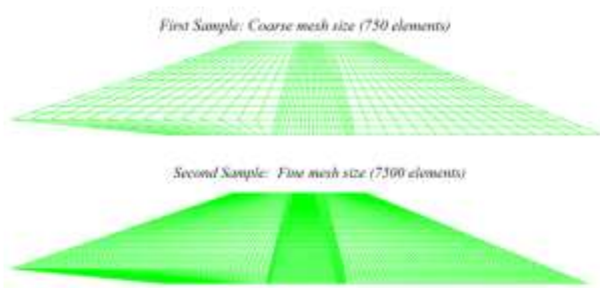


Figure 15: First and second samples' meshing

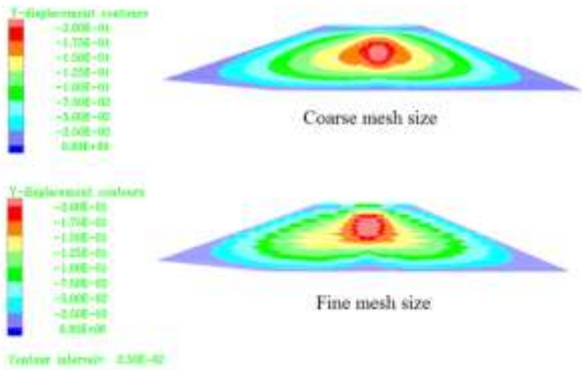


Figure 16: Vertical displacement of the first and the second samples

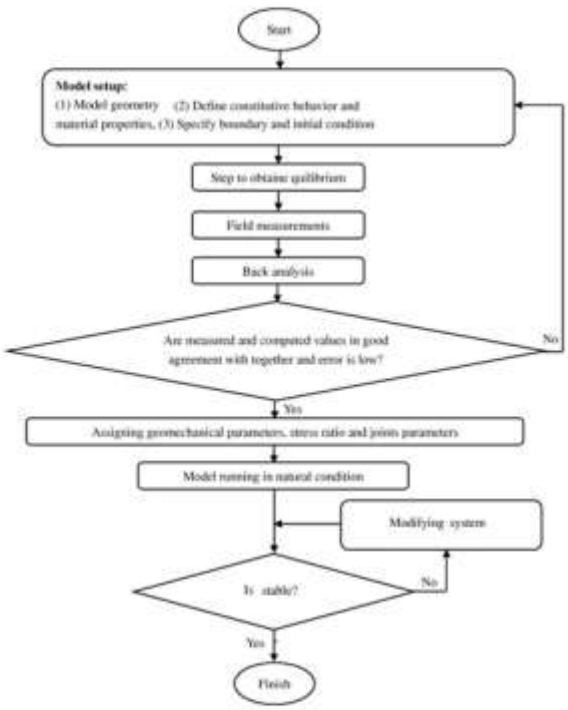
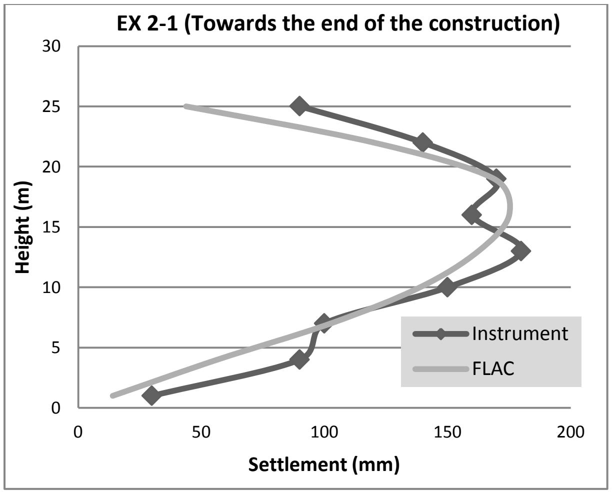
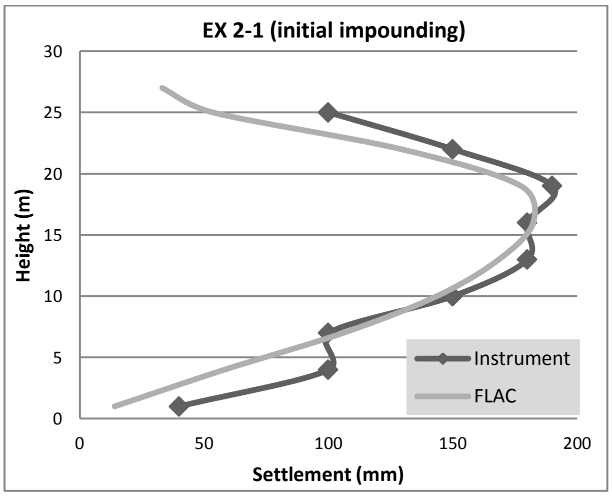
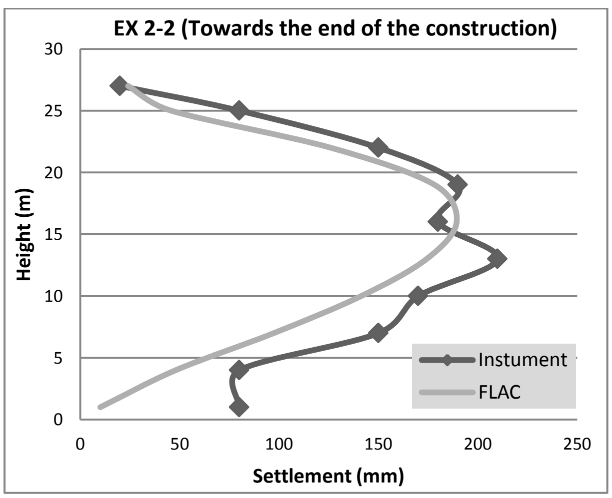


Figure17. Back analysis method and solution algorithm


EX 2-1 (Towards the end of the construction)
Height (m)
Settlement (mm)
Instrument
FLAC
0
5
10
15
20
25
30
0
50
100
150
200


EX 2-1 (initial impounding)
Height (m)
Settlement (mm)
Instrument
FLAC
0
5
10
15
20
25
30
0
50
100
150
200


EX 2-2 (Towards the end of the construction)
Height (m)
Settlement (mm)
Instument
FLAC
0
5
10
15
20
25
30
0
50
100
150
200
250

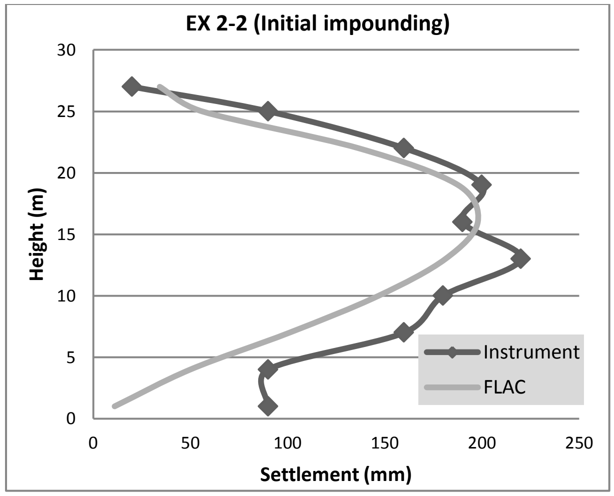


Figure18. Comparing the results of the instruments and numerical modeling in relation to Vertical displacement changes in the upstream (EX 2-1) and downstream(EX 2-2) height of the central core towards the end of the construction operation and after the initial impounding

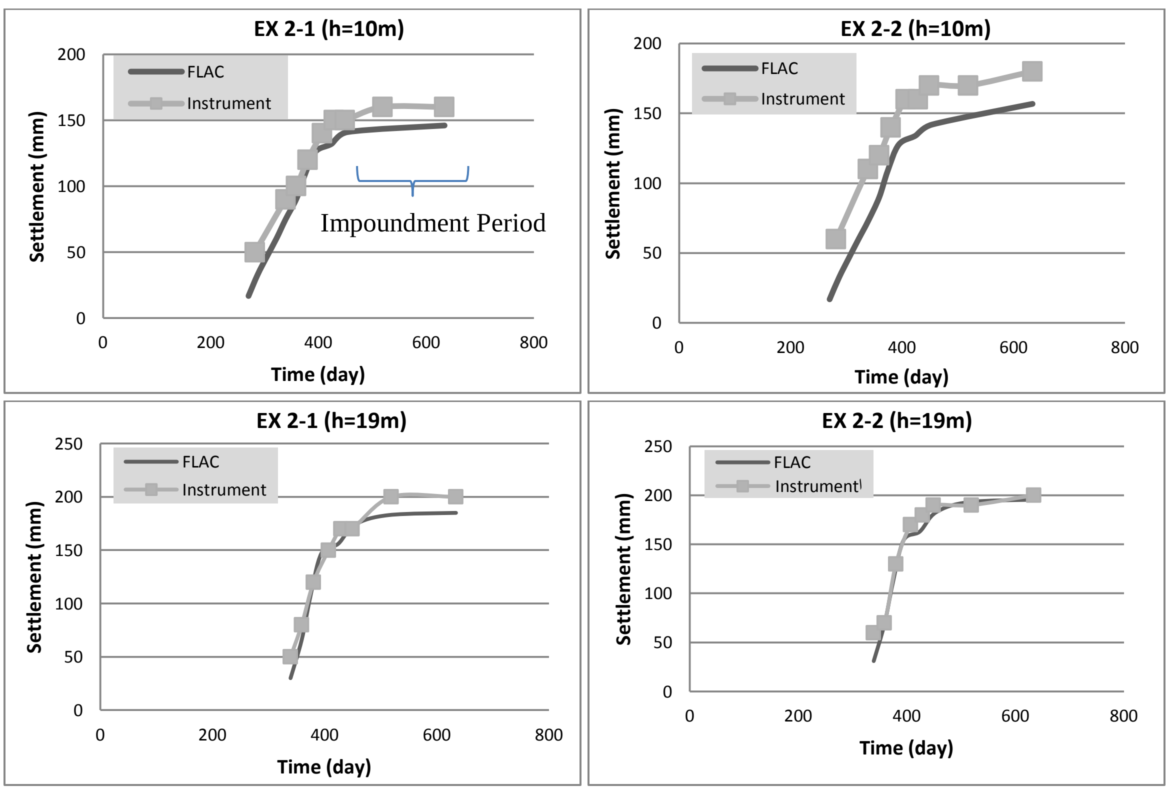


Figure19. Comparing the results from the inclinometers and numerical model in relation to the Vertical displacement changes in different levels of the dam with accordance to time

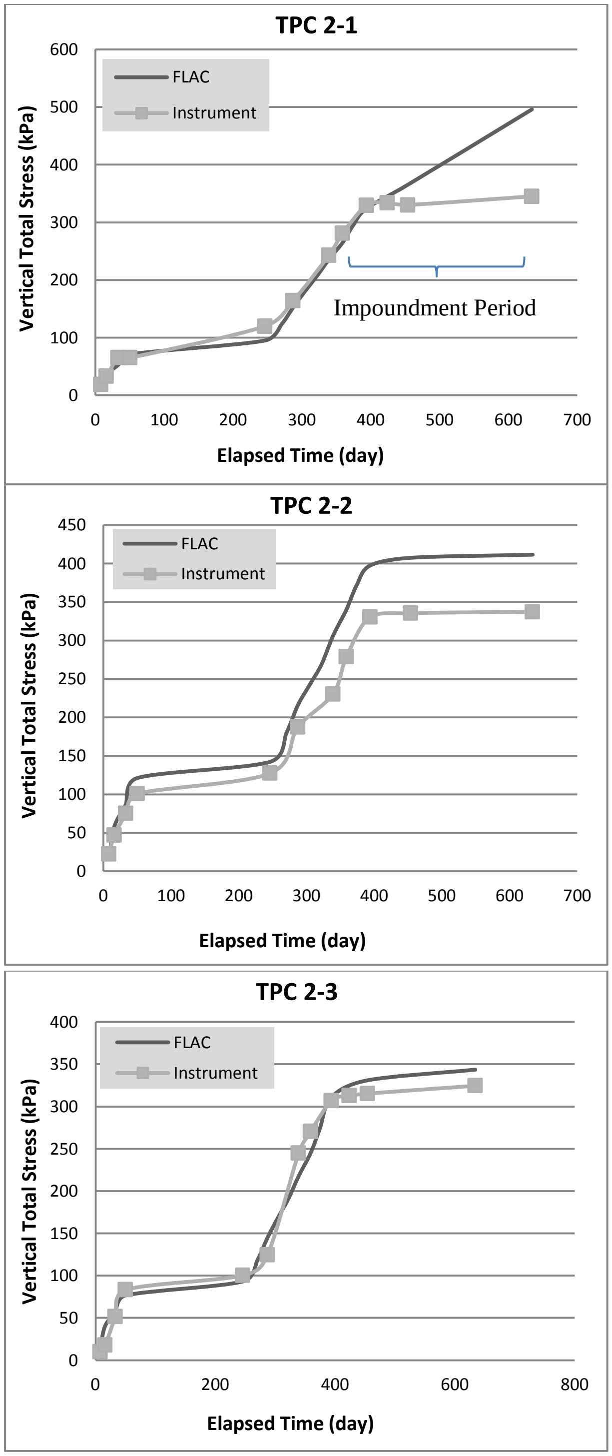


Figure20. Comparing the measurement results and numerical model in relation with the total vertical pressure in the piezometers located in the first level

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