30 Years Instrumentation Behavior of Srinagarind Dam and Analysis of Warning Criteria

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Abstract

The Srinagarind dam is the oldest and largest clay core rockfill dam in Thailand. During the service, the dam performed well with no serious incident. The records of instrumentation data were used to analyze the behavior of the dam in the past 30 years. Settlement and pore water pressure behavior was analyzed from settlement points and piezometers, respectively. The analysis of settlement was done by comparing the field data with various prediction methods. The analysis found that both clay core and rockfill material shows the secondary compression behavior. The dam is now settled closed to the calculated total settlement which including creep effect. As for the pore pressure behavior in clay core, the analysis found that the pore pressure, generated from compaction during construction, remained in the clay core during the early year of service. The result of the piezometers analysis was used as a constrain in seepage modeling. Seepage and stability modeling were done to simulate the defective behavior in each zone of dam and foundation that would be reflected in the reading of the piezometer. These values will be used as warning criteria for dam safety planning and emergency action plan. The modeling is also used to prioritize the piezometers in order to prepare the replacement plan in the future.

Introduction

The Srinagarind dam is a clay core rockfill dam with 17,745 million m^3 storage. The dam is located at Quae Yai river in Kanchanaburi province, about 190 kilometer northwest of Bangkok, Thailand. The dam has a height of 140 m from foundation rock and a crest length of about 610 m as shown in Figure 1. The center clay core is covered by series of fill material consisting of filter layer, transition fill and rockfill. The dam found on riverbed foundation is about 210 m long. So valley shape ratio of the dam equals to 1:1.6, therefore dam can be modeled under plain strain condition.

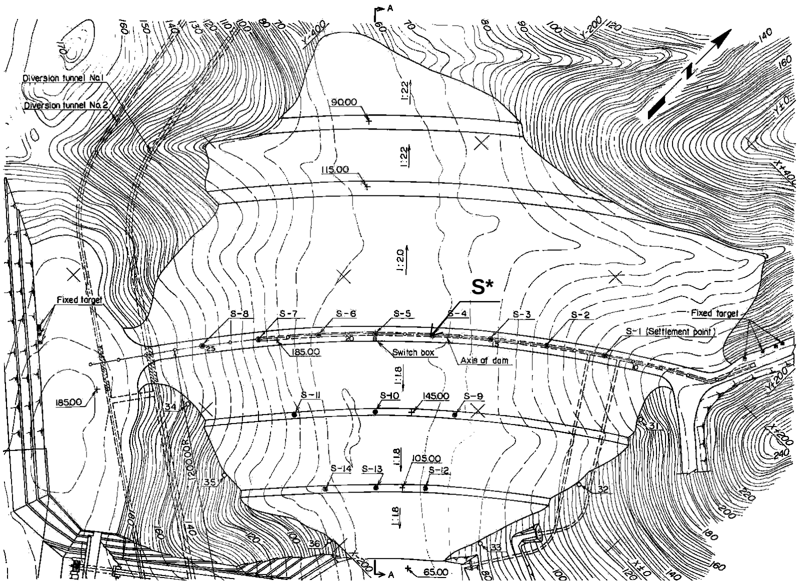
The construction of the dam commenced in 1976 and finished in 1978. The reservoir begun first filling in 1977 and fulfilled in 1981. During service, several earthquakes around 400 km away from dam site were measured. The maximum magnitude of 5.9 caused by reservoir triggered is recorded in worldwide. Figure 2 shows the earthquake events comparing with reservoir level since the first triggered in 1983. It can be seen that the earthquake gradually decreases its magnitude and frequency in later year.

Instrumentation

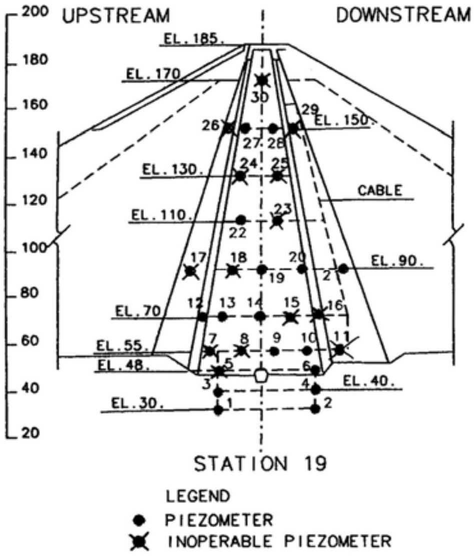
Dam instruments which used for measuring settlement, pore pressure and seepage are considered in this paper. Many instruments were installed since construction period and later on replaced when expired. Not all instruments had been replaced, only the necessary one has done. The type and location of the instruments are summarized in Table 1. Location of settlement points installed along dam crest and downstream berms are shown in Figure 1a. Thirty pressure transducers were installed in the same section at STA 19+00 (Figure 1d). Additional pressure transducers were installed at downstream of grouting curtain. After the dam had operated for 15 years, some sensors started to malfunction. In 2004, 5 open standpipe piezometers and 8 pressure sensors in the foundation gallery were installed to substitute the damaged sensors. Instrumentation data has been analyzed in this paper in order to understand the dam behavior and also determine the reading and maintenance concept in order to minimize maintenance cost and maximize safety of the dam.

TABLE 1: PRESENT STATUS OF THE INSTRUMENTS

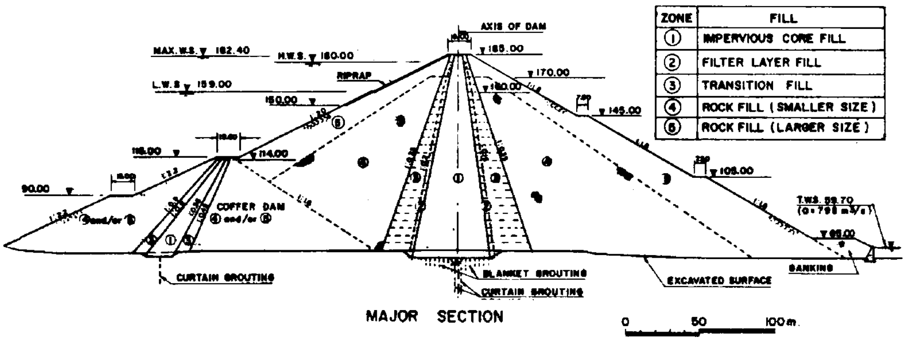
Type of instrument	Location	No. of instrument	
		Installed	Operated
Settlement points	On dam crest	9	9
	On downstream berms	6	6
Pore pressure transducers	Sta. 19+00	30	10
Additional pressure cells	Downstream of grouting curtain	32	14
Open standpipe piezometers	Downstream of clay core	5	5
V-notch weirs	Gallery	10	10



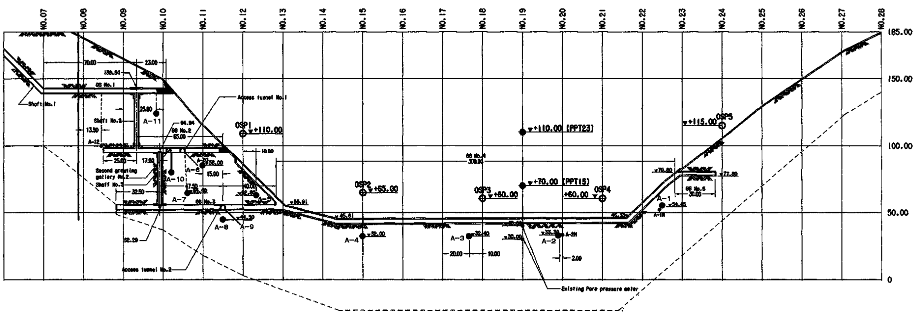
(a) Plan



(d) Location of pressure transducers



(b) Maximum dam section



(c) Profile at dam axis

Figure 1: Plan and section of Srinagarind dam

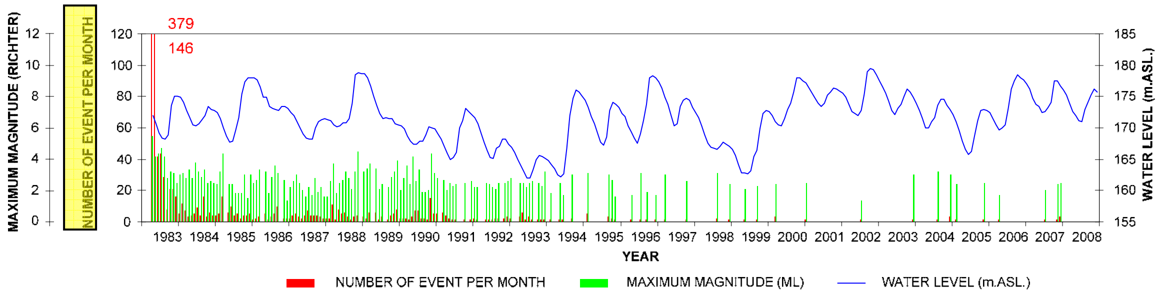


Figure 2: Frequency of earthquake event around Srinagarind dam from 1983 to 2008

Settlement behavior of dam

Methods for prediction

The settlement of the dam was monitored after the points installed. The initial reading is set for zero. In order to predict the total settlement of dam crest (S-1 to S-8 and S*) and downstream rock berms (S-9 to S-14) and time of the settlements, the following techniques are applied:

1. Rectangular hyperbola method (RHM) is recognised in consolidation test as Taylor's root time and semi-logarithm plot. This method assumes that change of consolidation with time limit to zero. Root time and semi-logarithm are used for predicting the primary consolidation of the clay core, but not for rockfill material.

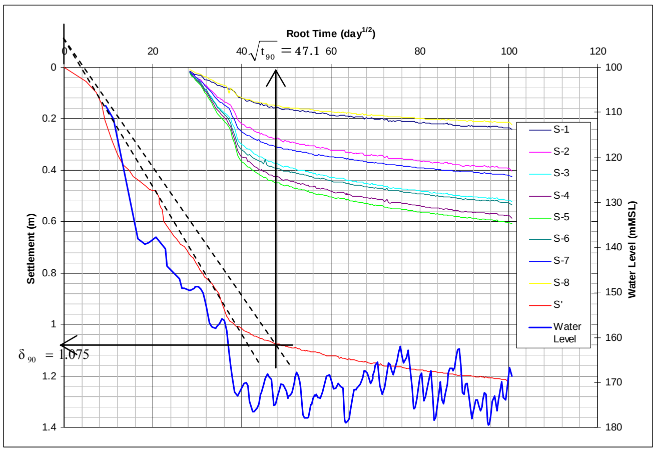


Figure 3: Tayler's root time plot

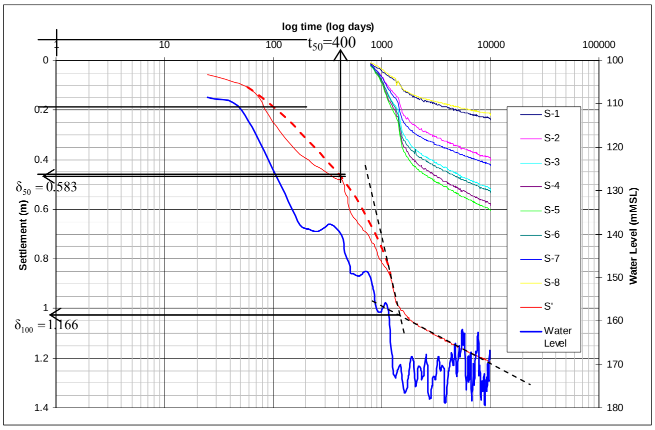


Figure 4: Semi-logarithm plot

2. Asaoka's plot [1] were done by two sets of present settlements, S_i and previous settlement, S_{i-1} in specific interval time. Linear regression of settlements were done in Figure 5 and gave a prediction equation with initial settlement, β_0 and slope of plot, β_1. Equation (1) is given and primary consolidation, S_∞ can be determined by Equation (2).

$$S_i = \beta_0 + \beta_1 \times S_{i-1} \quad (1)$$

$$S_\infty = \beta_0 / (1-\beta_1) \quad (2)$$

Note that Asaoka's plot gives only primary consolidation but not include immediate settlement and time of the settlement can not be estimated by this method.

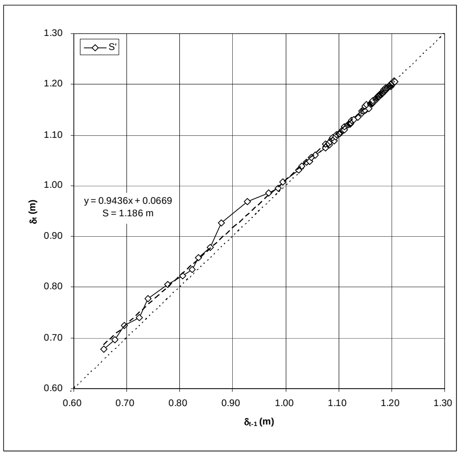


Figure 5: Asaoka's plot

3. Hyperbolic plot [2] assumes that rate of settlement constantly decrease with time. The slope of hyperbolic plot in Figure 6 is the inverse of settlement.

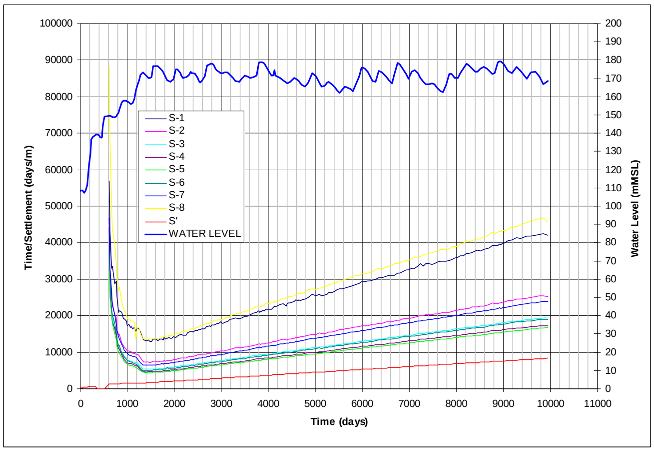


Figure 6: Hyperbolic plot

4. First-Order Rate Equations (FORE) was introduced by [3] to predict settlement of geotechnical engineering structures. This method assumes that the difference of settlement from the final settlement, $(S-S_u)$ decrease with time proportional to the difference as in Equation (3). Difference of settlement is formulated in term of natural logarithm of time in Equation (4). By best fit linear regression, the final settlement is predicted as shown in Figure 7.

$$- d(S-S_u)/dt = k(S-S_u) \quad (3)$$

$$\ln(S-S_u) = -kt + C \text{ or } \log(S-S_u) = -k_{10}t + C_{10} \quad (4)$$

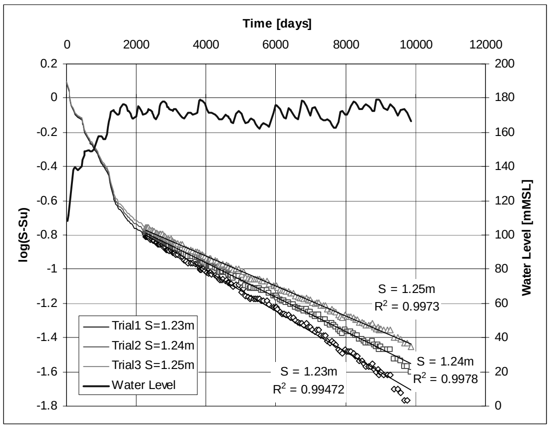


Figure 7: First-Order Rate Equation

Results of settlement analysis

Table 2 summarizes the maximum predicted settlement at both dam crest and downstream berms. The crest settlement from RHM and Asaoka's plot is between 1.166 and 1.194 m Hyperbolic plot and FORE give total settlement of about 1.195 to 1.240 m. Secondary consolidation can be found out about of 0.001-0.074 m. Similarly the percentage of settlements of rock berms have almost completed in range of 95 and 97%.

TABLE 2: PREDICTED SETTLEMENT OF SRINAGARIND DAM

Method	Dam crest	Downstream berms	
	+185 m ASL.	+145 m ASL.	+105 m ASL.
1. Rectangular Hyperbola Method			
- Root Time plot	1.194 (7,570)*	-	-
- Semi-logarithm	1.166 (1,300)	-	-
2. Asaoka's plot	1.186	1.188	0.335
3. Hyperbolic plot	1.195	1.310	0.372
4. First-Order Rate Equation	1.240 (12,300)	1.260 (14,150)	0.376 (15,500)
5. Actual reading on August 2005	1.220	1.222	0.359

* The numbers in brackets are the time of settlement in days.

According to the result of the predictions, the crest settlement of the dam due to primary consolidation found to be completely reached. The rest of settlement less than 0.1 m is probably caused by secondary compression. It therefore concludes that the designed camber is still adequate to the further settlement.

Pore pressure and seepage behavior

Measured pore water pressure in dam body is illustrated in contour of pressure head to investigate the distribution of pore pressure at the highest water level in that year (about 100 m from dam base). The excessive pore pressure induced by compaction in construction stage was clearly shown in Figure 8. There was a pocket of pressure at middle of core zone at +90mASL (P14) which presented 2 years after construction. Six years later (1982 to 1988), most of the pressure had dissipated from the clay core. The pore pressure at middle of the core reduced to 90 m.

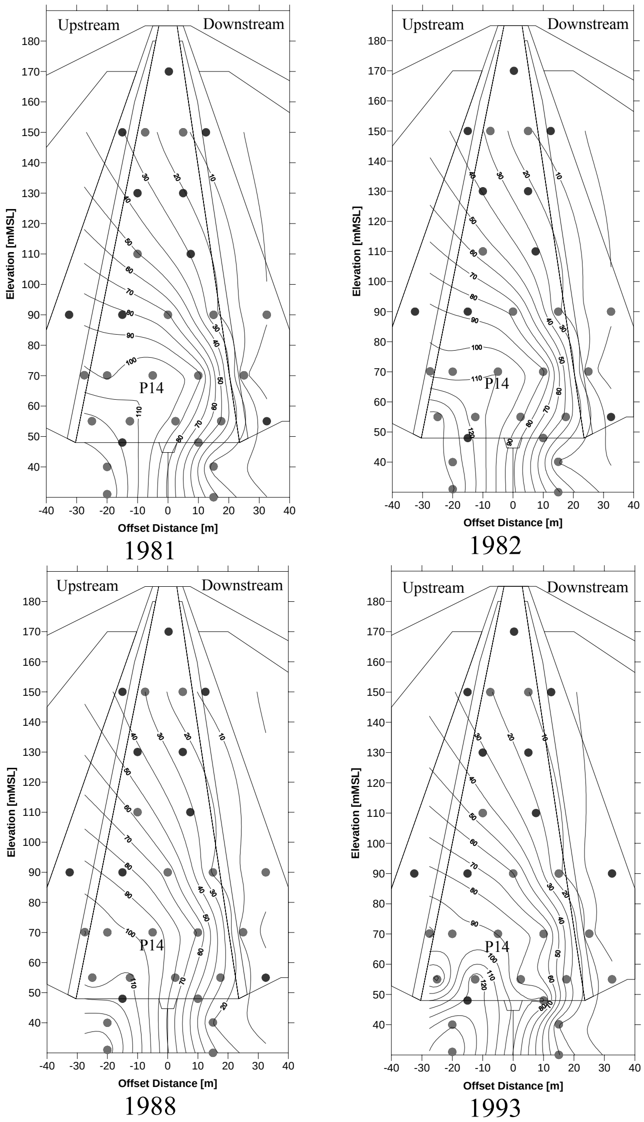


Figure 8: Distribution of pore water pressure in clay core

Concerning with piping, hydraulic gradient should be estimated. Figure 8 shows narrower space between contour lines which indicates higher hydraulic gradient along the interface of clay core and filter. Changes of hydraulic gradient at +55, +70 and +90 mASL are illustrated in Figure 9. The highest hydraulic gradient of about 6 can be observed at +70 mASL. It might be because of the excessive pore pressure due to compaction. When all pressure was dissipates in 1988, hydraulic gradient seem to decrease gradually with time. But hydraulic gradient at +55 and +90 mASL slightly changed in average of 3.5 and 3 respectively. The increase of hydraulic gradient at +70 mASL in 1988, and at +50 and +90 mASL in 1998 indicate the possibility of fine particles washed out in clay core. It is therefore recommended to monitor this behavior closely. Pressure sensors P9, P10, P15, P16, P19 and P20 need to be used to continue the monitoring.

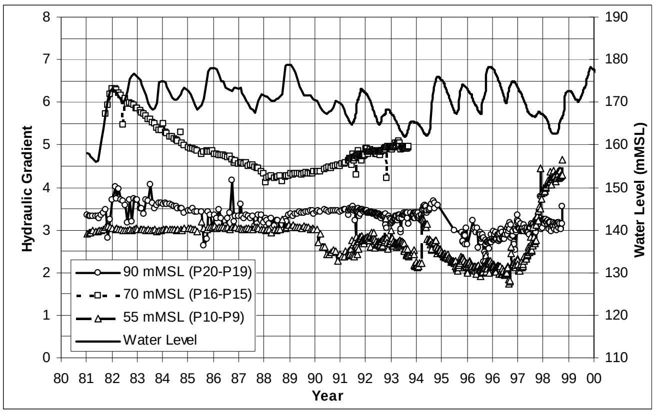


Figure 9: Changes of hydraulic gradient near interface of clay core and filter with time

Seepage through dam foundation is able to be measured partially by V- notch weir (SEP-6) which installed in the dam gallery. Figure 10 shows that rate of seepage tended to decrease with time after first filling, until 2003 the seepage started to directly depend on water level (dash circle in Figure 10). This behavior might indicate that the joint of concrete gallery wall was gradually sealed since the early of reservoir filling, but when water level in the reservoir rises up higher than the past record, the plugged particles are washed out and it probably conducts more seepage.

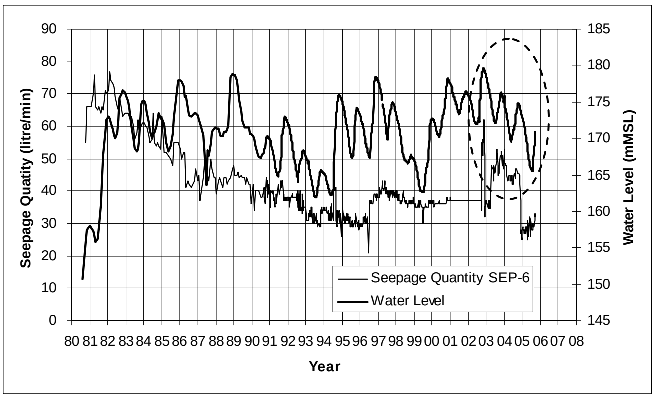


Figure 10: Seepage through the gallery

Seepage modeling for setting up the warning criteria

The warning criteria used for indicating the unusual seepage through dam body is established based on results of various cases of seepage analysis. The maximum section of dam is modeled at full water level of +180 mASL and with downstream water level of +55 mASL. Hydraulic conductivities of materials used for models are concluded from field permeability testing report. Case of present condition of clay core and filter properties (Case 1) is modeled and verified with present pore pressure data. Another 5 cases (Case 2 to 6) are modeled under anomalous condition of clay core and filter layer. The hydraulic conductivities, k used for each case are summarized in Table 3. Results of pressure head are shown in Figure 11.

TABLE 3: HYDRAULIC CONDUCTIVITY OF MATERIALS

Materials	k (10^{-4} cm/sec) for each case					
	1	2	3	4	5	6
Clay core	0.1	1	10	0.1	1	10
Filter layer	10	10	10	100	100	100
Rockfill	1000					
Grouting curtain	0.5					
Foundation rock	2 – 6					

Clay core hydraulic conductivity of 10^{-5} cm/sec (Case 1) gives the decrease of pressure head at dam base (P5 and P6) from 128.2 to 19.0 m (about 109.2 m of difference), while the observed pressure head decrease from 130 to 20 m. The hydraulic gradient close to the interface of clay core and filter equals to 3. The model for normal case has been satisfied.

The performance of clay core can be evaluated by pressure head reduction. The clay core with k of 10^{-4} cm/sec does not affect on pore pressure. The less impervious clay core in Case 2 and 5 causes the rising up of downstream water table of about 7 – 12 m from dam base which is similar to case 1 and 4. For the extreme anomalous case where clay core (case 3 and 6) with k of 10^{-3} cm/sec causes the water level rising up 31 – 33 m from the dam base. Also dangerous exit gradient at dam toe is gained.

In order to prepare the warning criteria for critical cases, pore pressure values at the positions of field piezometer were used for different warning level as shown in Table 4. Furthermore, observation well is recommended to be installed in downstream slope to measure the water level and observe the leakage due to internal cracking.

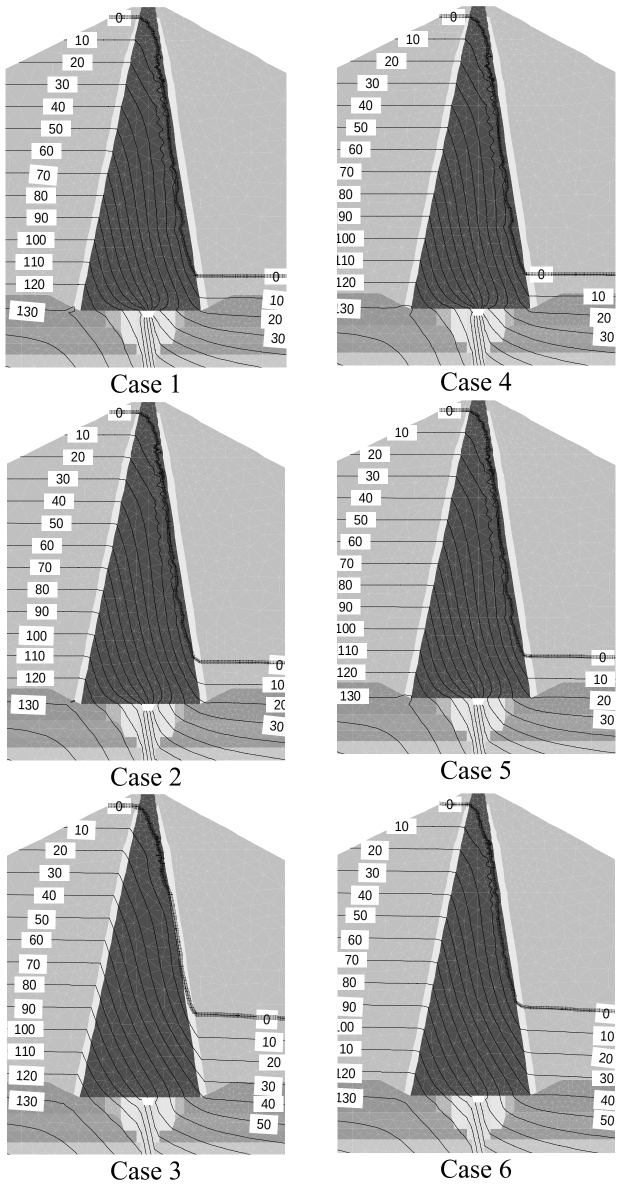


Figure 11: Pressure head within clay core from analysis

TABLE 4: WARNING LEVEL FOR EACH ANALYZED CASE

Warning Level	Analyzed Case	Action
Normal	1 and 4	Regular measure
Abnormal	2 and 5	Lower reservoir level
Critical	3 and 6	Lower reservoir level and evacuation plan

Conclusion

The 30 years old Srinagarind dam, the oldest and largest clay cored rockfill dam in Thailand, has been investigated its behaviors by dam instrumentation. Dam instrument analysis indicates settlement and seepage behavior of the dam. The dam has been completely settled and the designed crest elevation is adequate to the further settlement. All excess pore pressure induced by compaction dissipated in first 8 years after construction. The pore pressure due to seepage through the dam is later on concentrated at lower part of dam. Seepage analysis is used to model the unusual seepage behavior of the dam when there is any problem on permeability of clay core and filter layer. The warning criteria has been set up based on the field data and the seepage analysis results.

Acknowledgements

The authors would like to thank Electricity Generating Authority of Thailand (EGAT) for supporting fund under stability analysis of SNR dam project and for providing the useful instrumentations data.

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