BEHAVIOR OF A HIGH ROCKFILL DAM WITH CLAY CORE DURING NINETEEN YEARS OF OBSERVATION

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ABSTRACT

In order to be confident about normal behavior and safe operation of dams or to find possible reasons for their potential abnormal behavior, their monitoring is a must. In this paper, monitoring results from the instrumented sections of the Masjed-Soleyman rockfill dam with a clay core (177m high and 497 m long dam crest) have been studied and the dam behavior is evaluated based on the results. The paper concentrates on the dam behavior during the nineteen years of post construction period. The surface displacement benchmarks located on the dam crest and downstream slope and also the settlement gauges installed within the dam core show relatively large deformations. Moreover, the history of pore water pressures in the core, measured by the installed piezometers, indicates that the dissipation rate of pore water pressures within the core has been very low during almost the last two decades. Considering the dam dimensions and its 3D behavior, the results are evaluated, cross-checked, and interpreted. Finally, conclusions are made regarding the general behavior of the dam.

1. INTRODUCTION

The behavior of a high rockfill dam with a clay core constructed in a narrow canyon is complicated and depends on a number of parameters, including materials of different zones and geometry of the dam, geometry of the canyon and the bearing capacity of the rock mass foundation. The rate of deformations of the dam is usually stabilized sometime in the post construction period. Some rockfill dams in the class of the Masjed-Soleyman dam have reached negligible rates of deformation a few years after their construction and impounding despite undergoing large deformations and/or some abnormal behavior during their life (Hunter & Fell 2003, Marsal & Ramirez de Arellano 1972, Moreno & Alberro 1982, Nakagawa et al.1983). The Masjed-Soleyman dam is still under transient seepage and the dam body has also faced large deformations in the post construction time. The main objective of this study is to evaluate the dam behavior through reviewing and assessment of monitored data from different instruments installed on and within the dam body. The data are obtained from surface benchmarks, settlement gauges, total pressure cells and piezometers.

2 GENERAL CHARACTERISTICS

The Masjed-Soleyman rockfill dam with clay core is one of the highest dams (with maximum height of 176 m) in Iran, which was constructed between 1995 to November 2000 and was impounded one month after the end of construction. The first impounding was carried out in five stages until 22-June-2002 and the reservoir was kept almost constant in the operation time (Figure 1). More details on the dam's characteristics during construction and first impounding can be found in (Soroush 2011). The longitudinal and highest cross sections of the dam are shown in Figures 2 and 3, respectively.

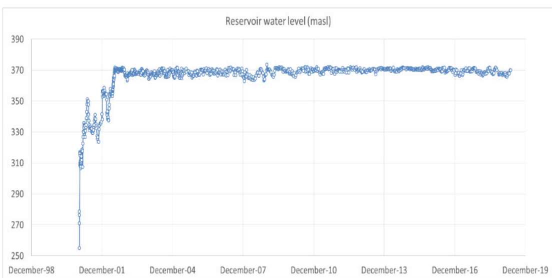

Figure 1 : Impounding history of the Masjed-Soleyman dam

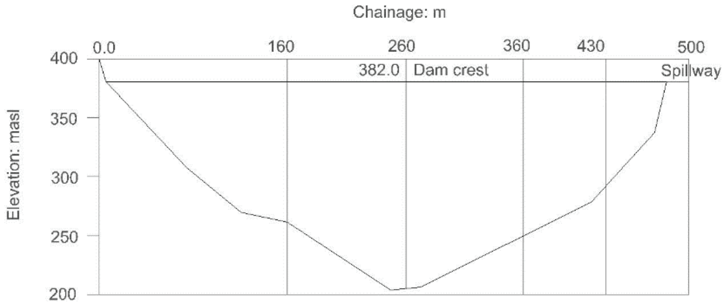

Figure 2 : Longitudinal section of the Masjed-Soleyman dam (view from upstream)

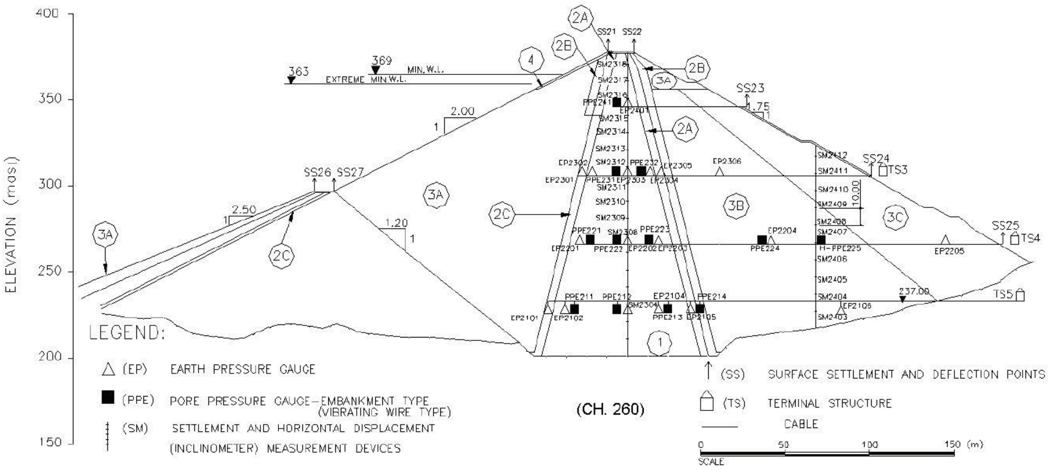

Figure 3 : Instrumented highest cross section of the Masjed-Soleyman dam

Table 1 and 2 show the in-place characteristics of the core and shell rockfill materials, respectively.

Table 1 : Core material characteristics

Unified Soil Classification	Ave. dry density (kN/m^3)	Placement method	Ave. Moisture content
CL/GC	18.2	Well compacted-100mm layers	2% wet of OMC

Table 2 : Rockfill material characteristics

Source	dry density (kN/m^3)	Maximum particle size	Layer thickness (m)
Conglomerate	22.2-23.3	1 m	0.7-1.0 m layers after dry compaction

3. INSTRUMENTATION RESULTS

The Masjed-Soleyman dam was well instrumented, but some of its instruments were lost during construction, impounding and operation time. The followings are the typical results of the available instruments.

3.1 Displacements

Figure 4 shows the distribution of total settlements within the core for CH.260, which is the highest cross-section, with the maximum settlement of 3.7,4.7 and 6.5 m during construction, after first impounding and the operation period (until December 2010, after which the settlement gauge showing maximum settlement was lost) respectively.

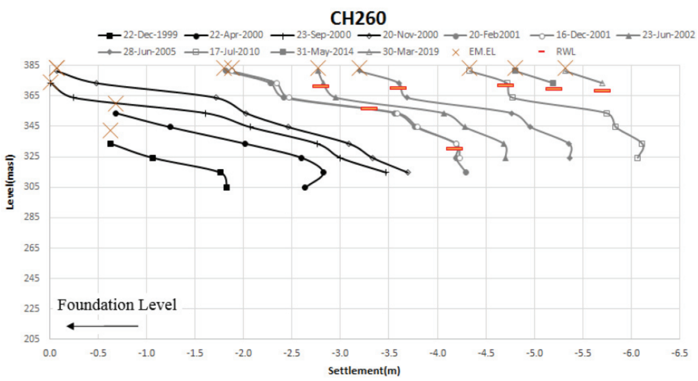

Figure 4 : Settlement distribution within the core for CH.260

It is noticeable that the higher elevations of the dam near the crest have experienced large displacements during the early stages of the first impounding and it has been continuing at the post construction period though the increasing rates are becoming less. It was suggested that saturation collapse of the upstream shell, which was executed dry during construction has caused the large settlements of the core during the first impounding (Soroush & Aghaei Araei 2006).

Figure 5 presents the magnitudes and directions of the horizontal surface displacements of the crest and the downstream shell of the dam from 1-April-2001 until 19-November-2018.

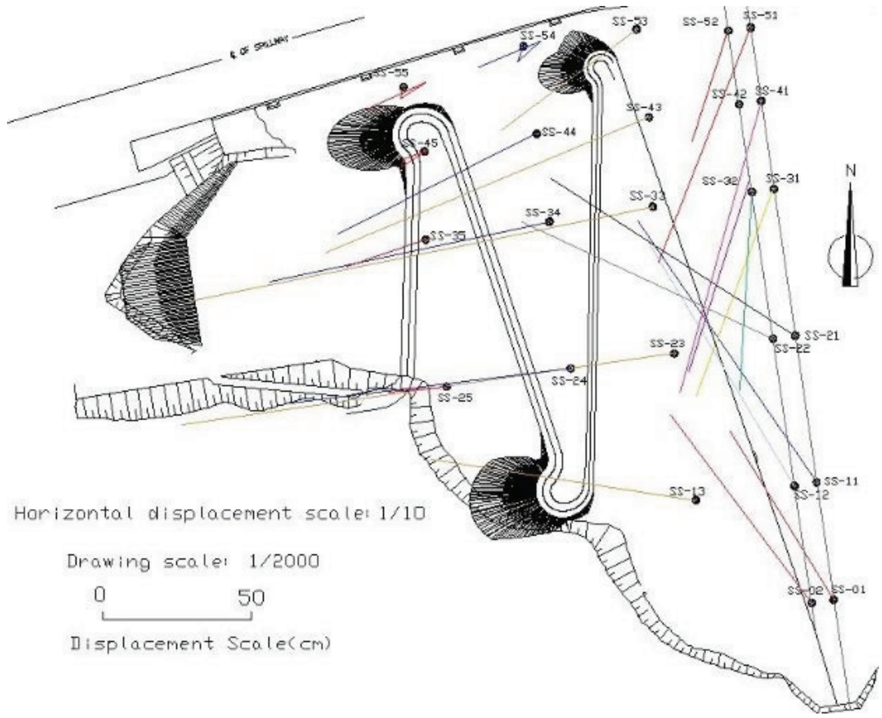

Figure 5 : Magnitudes and directions of the horizontal surface displacements of the crest and the downstream slope of the Masjed-Soleyman dam during first impounding and operation time

It is evidently shown that the crest of the dam has moved toward the valley center and the downstream shell has moved almost in-river direction. This is the typical behavior of dams located in narrow valleys.

3.2 Total stresses and pore water pressures

Figures 6a and 6b present variations of the total stress and pore water pressures for a number of points within the core for CH.260 during construction, first impounding and the operation period.

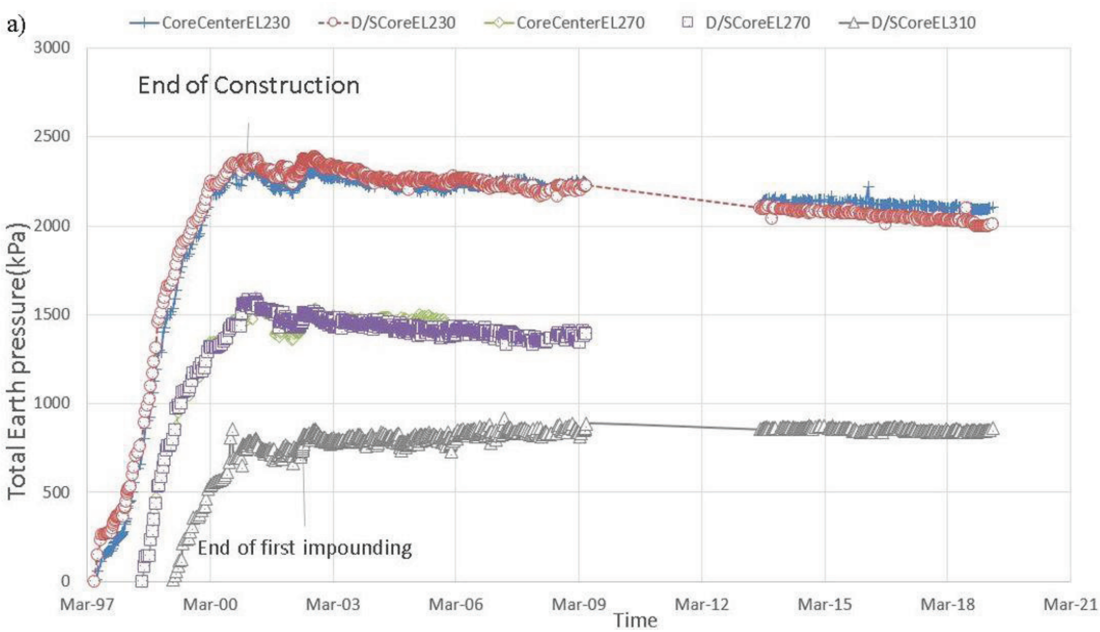

Figure 6 : (a) Variations of total pressures and (b) pore water pressures within the dam core for CH.260

Figure 6b indicates that the dissipation rate of excess pore water pressures, induced during construction and first impounding is very low and that the pore water pressure are still in transient conditions. The low dissipation rate of the core suggests that the core is in an almost undrained conditions. This phenomenon can be attributed to the low permeability of the core material and on-going deformations of the dam; the latter yields loading on the core.

As can be seen in Figure 6, total stresses and pore water pressures in EL.230 and EL.270 have slightly decreased (due to partial consolidations); while in EL.310 total stresses have increased and the pore water pressures have been almost constant after the end of first impounding. In order to investigate the increase of total stresses in the upper elevations of the dam core , the normalized total stresses of the downstream core in EL.310 (with respect to the end of construction total stresses) are summarized in Table 3 for different chainages of the dam.

Table 3 : Normalized total stress for different chainages during time

Time	CH.160	CH.260	CH.360	CH.430
End of construction	1	1	1	1
End of first filling	1.09	1.16	1.14	0.99
17-July-2005	1.05	1.18	1.13	0.99
13-May-2009	1.07	1.28	1.23	0.99
10-April-2019	1.08	1.24	1.24	1

It is inferred from Table 3 that total stresses have increased by time. The exception is CH.430 in which total stresses remained almost constant. CH.260 (where the dam height is maximum; refer to Fig. 2) have experienced the most increases of total stresses. By comparison of total stresses in Table 3 and horizontal surface displacements in Figure 4, it can be concluded that the tendency of the dam body to move toward the center of the valley has been the cause of continuous loading on the core in the post construction time.

The history of pore water pressure ratios in a number of points of the core for CH.260 are computed according to Equations 1 and 2 and summarized in Tables 4 and 5.

$$r_u = \frac{u}{\gamma h} \tag{1}$$

$$R_u = \frac{u}{\sigma_v} \tag{2}$$

Where u = measured pore water pressure; γh = computed overburden; and σ_v = measured total stress.

Table 4 : Pore water pressure ratio, r_u, in the core for CH.260

El. (masl)	End of construction		End of first impounding		May 2009		April 2019	
	Center	Downstream	Center	Downstream	Center	Downstream	Center	Downstream
310	-	0.3	-	0.41	-	0.41	-	-
270	0.56	0.6	0.61	0.65	-	0.61	-	-
230	0.64	0.69	0.67	0.68	-	0.65	-	0.58

Table 5 : Pore water pressure ratio, R_u, in the core for CH.260

Elevation (masl)	End of construction		End of first impounding		May 2009		April 2019	
	Center	Downstream	Center	Downstream	Center	Downstream	Center	Downstream
310	-	0.71	-	0.83	-	0.75	-	-
270	0.97	0.99	1.02	1.03	-	1.04	-	-
230	0.95	0.9	0.96	0.87	-	0.9	-	0.89

A comparison of the values of pore water pressure ratios of Tables 4 and 5 shows obviously that R_u values are higher than their corresponding values of r_u. In addition, the values of pore water pressure ratios in the center of the core and in the downstream of the core are almost equal. Also the values of Ru are very high in the core (especially in lower portions of the dam) and consequently, the effective stresses and the shear strengths are low in these regions. It may be concluded that due to constant volume behavior of the core (especially lower elevations which behave in undrained conditions), the lower weak elevations have experienced lateral displacements under loading induced by settlements of upper elevations of the dam.

Having three-component earth pressures in each cluster in the body of the Masjed-Soleyman dam, it is possible to determine the principal stresses in the plane perpendicular to dam axis. The ratio of σ'_3 to σ'_1 is the coefficient of lateral earth pressure, k, which is an indicator for the evaluation of horizontal displacements in the dam, especially in the core. If "k" increases the magnitude of horizontal displacement decreases and the soil approaches passive pressures, and vice versa. The ratio of σ'_3 to σ'_1 for some points in the core for CH.260 are shown in Figure 7.

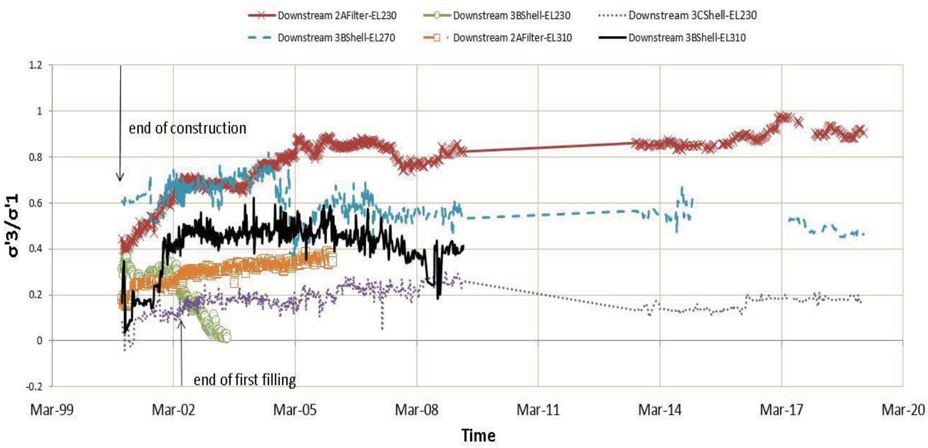

Figure 7 : Ratio of σ´3 to σ´1 in the core for CH.260

It is evident in Figure 7 that ratio of σ'_3 to σ'_1 is decreasing in the downstream 3B shell material in the operation time, despite being constant or increasing in other materials of the dam. So it may be concluded that the downstream 3B material has been approaching active pressure conditions and has exerted latter forces on the neighboring zones during the dam operation time.

Based on Figure 6, Table 4 and 5, one may conclude that the high values of post construction displacements of the dam (as shown in Fig. 4) are not due to the consolidation of the dam core, but it is thought to be the result of saturation collapse of the upstream shell during the first impounding, and the continuous loading on the core due to the dam axis direction movement of the core toward the center of valley (Fig. 5 and Table 3) and the exerted active pressure from 3B shell material to the neighboring zones (Fig. 7).

4. CONCLUSIONS

In order to understand the basic reasons of the relatively high deformations of the Masjed-Soleyman rockfill dam, the instruments installed on and within the dam body were carefully studied and the deformation mechanism of the dam during first impounding and operation time was evaluated. It is learnt from this case study that the undrained condition of the core (due to the low permeability of the core material) followed by continuous loading on the core during the post construction period has led to the continuous high deformations of the dam in the post construction period. The continuous loading has been induced by a number of factors, including the fact that the dam is located in the narrow valley and the typical behavior of these dams is to move toward the center of the valley and also probably because the downstream shell has been in active pressure conditions.

ACKNOWLEDGMENT

The authors would like to thank Mr. Arman Maddah for his help and providing data for studying the Masjed-Soleyman dam.

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