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The Consolidation Behavior of the Clay-Core in a Rock Fill Dam — Atatürk Dam Case Study

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THE CONSOLIDATION BEHAVIOR OF THE CLAY-CORE IN A ROCK FILL DAM - ATATÜRK DAM CASE STUDY

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ABSTRACT

Unexpectedly large settlements occurred in the 165 meter high clay core of Atatürk Dam during the reservoir filling stage. An investigation was conducted based on laboratory experiments and numerical analysis. Consolidation tests were performed on compacted samples under stress levels expected to take place in the field by considering the possible factors affecting the consolidation behavior. The experimental findings were used to model the observed settlements based on a parametric study and by back-calculation. The total expected settlements were determined to be in the order of 16.0 m. While a good fit was captured between the observed and modeled settlements prior to the reservoir filling, it was not possible to model the significantly large settlements observed within the clay core located approximately 120 meter below the crest following the reservoir filling. Evaluating other observations and findings, it was concluded that this phenomenon could be attributed to the lateral displacement of the core material into the filter and shell zones that were prone to instabilities due to disintegration under water.

INTRODUCTION

The evaluation of strength and compressibility properties of clays used in the core of embankment dams and the final estimation of the expected settlements constitutes a crucial step for dam engineering. This study focuses on the investigation of the settlement and consolidation behavior of 165 meter high clay core of Atatürk Dam that was constructed in southeast region of Turkey. This is a rock fill dam with an impervious clay core and the filter and shell zones that are composed of alluvial material and mainly basalt respectively. The length of the crest is 1914m and the total height of the dam is 184m from the foundation level. Immediately following the reservoir filling, unexpectedly large settlements were observed. A longitudinal crack was formed along the central region of dam body between the crest and the downstream riprap. This case was investigated through an extensive laboratory study and calibration of laboratory measurements by a parametric study and back-calculation with respect to recorded settlements acquired from the settlement plate network located at different depths in the dam body.

DEFORMATIONS IN EMBANKMENT DAMS

There are various analytical and experimental studies carried out for the calculation of displacements and settlement-time behavior of embankment dams (Clough and Woodward, 1967; Charles, 1976; Cavounidis and Höeg, 1977; Penman et al., 1971; Eisenstein and Law, 1977). Previous studies revealed that a pertinent calculation of displacement and consolidation requires an extensive laboratory testing which should be in accordance with the stress levels and stress paths expected to occur in the dam body during various phases of construction and operation. Within this framework, the main imposing field conditions should be considered as the high stress levels and the interaction of dam material with water. The non-homogeneities in the compressibility and permeability of the fill material may result in non-uniform pore pressure build-up and consolidation response while differential settlements between different material zones may lead to local stress concentrations. Another source of differential settlement is the degradation of upstream fill materials following the fill of reservoir. The grain size distribution of soils does change under high stresses causing a decrease in shear strength and an increase in excessive displacements. The sophisticated displacement measurements conducted at El Infiernillo Dam in Mexico revealed very significant settlements in the rock fill material during the post-construction period. It was suggested that the degradation and crushing of the rock fragments under water action and thereby continuous change in the stability of the fill should be responsible for this phenomenon (Marsal and

Arellano, 1967). Squier (1967) stated that the displacements observed in the core and downstream fill and the transversal cracks at the crest of 135 meter high rock-fill Cougar Dam were related to stress transfer caused by differential displacements between different zones of the dam body. Penman and Mitchell (1970) observed that relatively larger settlements of the clay core with respect to the rock-fill of Scammonden Dam resulted in additional lateral stresses and shear deformations in the clay core that in turn led to excessive local displacements in the filter and rock material covering the clay core. This process caused a lateral extension in the clay core which also shows that shear strength was exceeded.. This case suggests that the clay core is also prone to loss in the shear strength under high stress levels. Ansal et al. (1989) found out that a 50% strength loss after a certain level of stress intensity occurs for cohesive soils.

MATERIAL PROPERTIES

The clay soil used in the core of Atatürk Dam has average Atterberg limits of LL_{avg}=57, PI_{avg}=32 with 6% coarse particles that can be classified as lean to fat clay (CL-CH). A series of standard Proctor tests were conducted and average of maximum dry density γ_{dmax} = 14.9 kN/m^3 and optimum water content w_{opt} = 25% were determined. Eight oedometer tests were performed on 80 mm diameter samples trimmed from compacted samples prepared at dry and wet sides of the optimum water content and with maximum dry density. Figure 1 depicts two of the oedometer test results where a high stress level of 2000 kPa was applied for the reproduction of the field conditions. It is clear that samples prepared at dry side and wet side of optimum did not show significantly different behavior. By submerging consolidation samples under water at various stages, it was observed that the clay was not of collapsible type. On the contrary significant swelling potentials were observed for stress levels smaller than 200 kPa indicating that secondary consolidation would not contribute significantly to the total expected settlements.

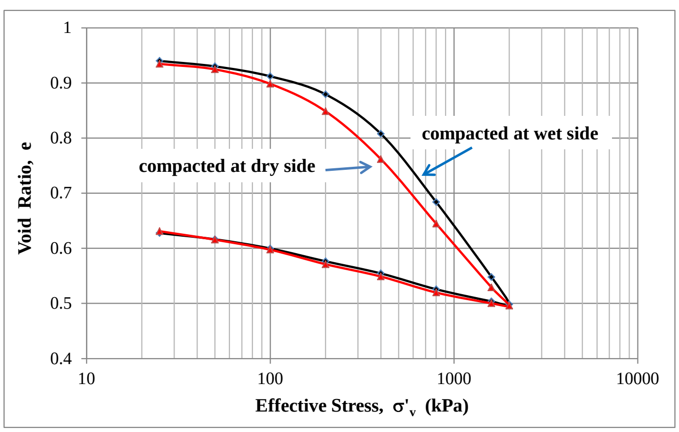

Fig. 1. The consolidation curves for samples compacted at dry and wet sides of the optimum water content.

The overconsolidation caused during the compaction stage should also be taken into account. Assuming that laboratory compaction can simulate the field, pre-consolidation pressure values were determined for each sample and it was determined that, σ'_p= 200-350 kPa. It should be noted that field compaction procedures may lead to higher pre-consolidation stress values.

SETTLEMENT CALCULATIONS

The fill construction of the core of Atatürk Dam was taken as monthly stages and the field schedule was followed as much as possible. Both volumetric compression values and compression and recompression index values were determined for the calculations by considering overconsolidation effect and the staged construction process.

Another aspect of the problem is the evaluation of the settlement-time relation and to determine the current degree of consolidation for the clay core. The calculations were carried out by treating each fill layer with respect to its time scale within the construction process. The shortest drainage paths both in the vertical and horizontal direction were considered and it was assumed that the coefficient of consolidation, C_v, is isotropic while the variation of C_v values with the stress level was taken into account for each layer. Casagrande and Taylor methods were used for the calculation of C_v values and it was determined that Taylor's approach estimates unrealistically low values. Following Casagrande method, the upper and lower boundaries for the degree of consolidation of the clay core by March 1993 were calculated as 97 % and 50 % respectively (Fig.2). By adopting and utilizing simple statistical analysis and assuming a normal distribution for the coefficient of variation of C_v, it was estimated that 70 % of the total expected settlements should have been completed by March 1993 with an exceedance probability of 70 %.

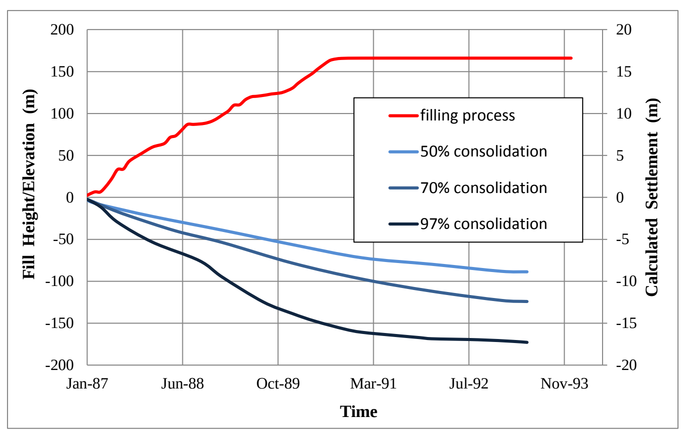

Fig.2. The progress of construction of the clay core fill and calculated settlements.

OBSERVED SETTLEMENTS

A settlement measurement network was installed by placing settlement plates located at several depths and points within the clay core (ATA Corp). The measurements indicated that there was a significant difference in the settlement behavior before and after the reservoir filling. As soon as the reservoir was filled with water very large settlements were recorded and the connections with the plates that were located at lower elevations of the core were lost which may be an indication of excessive displacements both along the vertical and horizontal directions.

The first attempt was made to model the settlements recorded at Station#21 during April 1990 and June 1990 prior to reservoir filling. The drastic difference between the observed and calculated settlements can be seen in Fig.3. Such a high discrepancy can be attributed to various factors. When the laboratory experimental findings are used in modeling observed settlements, the pre-consolidation pressure other than compression index and/or modulus of volumetric compression should be evaluated for such a deviation. The difference between field compaction and laboratory compaction mainly manifests itself with the difference in pre-consolidation pressure obtained from laboratory measurements and the actual field values. In addition, it is possible that there may exist 300 to 400 times difference between laboratory determined and field estimated C_v values.

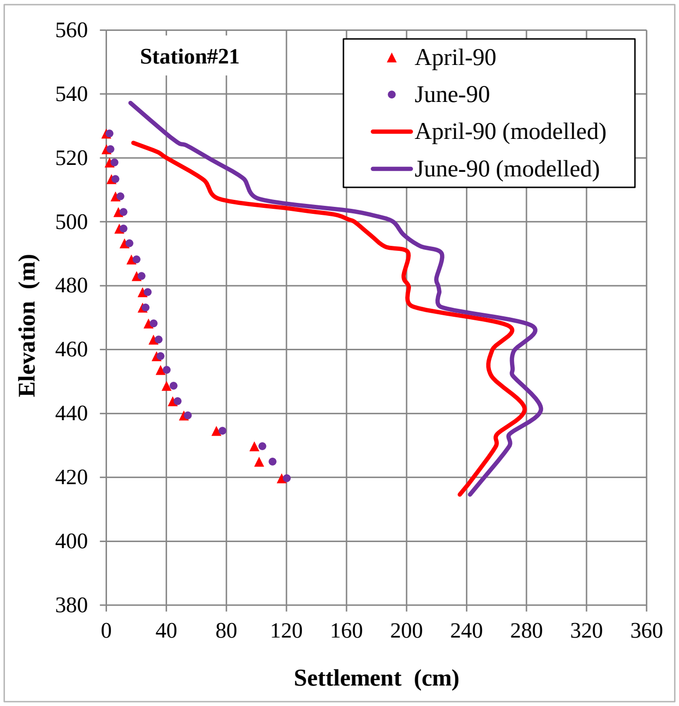

Fig.3. The observed and predicted settlements prior to reservoir filling at Station#21.

A back-calculation was performed by changing laboratory determined pre-consolidation and C_v values, and a much better fit was obtained with the observed settlements recorded at Station#13 at elevations higher than 440m as depicted in Fig.4. The back-calculated pre-consolidation pressure was 1000 kPa and C_v values were increased by 200 times in order to model the observed behavior.

But as can be seen in Fig.4, the excessive settlements recorded at the settlement plate at Elevation 440m cannot be modeled. This section is 120m below the crest and it is assumed that a lateral spreading under high vertical stress might be responsible for such an excessive settlement.

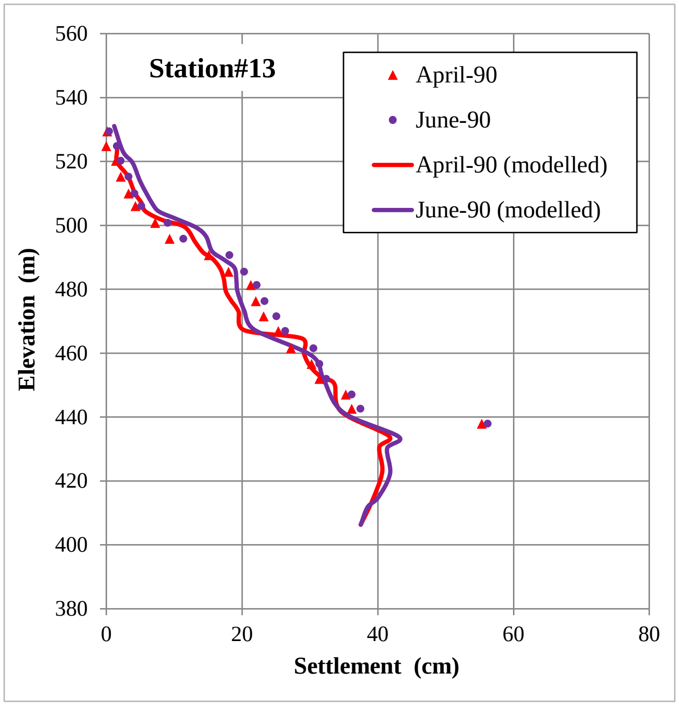

Fig.4. The observed and predicted settlements determined by back-calculation after reservoir filling at Station#13.

Even when the consolidation parameters were modified unrealistically to model the total recorded settlement data, it was not possible to model the settlements observed between the elevations of 480 and 440m as shown in Fig.5. Considering that one other explanation might be that different types of clays had been used for the fill. A parametric analyses were performed none of which still could capture the settlements recorded at around Elevation 440m.

It was observed that the settlements accelerated following the filling of the reservoir and within seven months between June 1990 and December 1990, unexpectedly large and almost immediate settlements occurred that could not be modeled with any known approach and analysis. This fact also supports the hypothesis that the lateral spreading of the clay core into the filter material and the shell zone could have caused the observed settlements. This hypothesis was later verified by Cetin et al. (2000) who conducted a petrographic and X-ray analysis, and stated that two different basalts were used in the rock-fill zone with the same primary mineral but with differing weathering states. The iron montmorillonites existing in highly altered olivines in the weathered vesicular basalt tend to expand on wetting resulting in the slaking of the vesicular basalt which in turn adding up to the total settlement of the dam and causing landslides both in the core section and rock-fill sections on the upstream side.

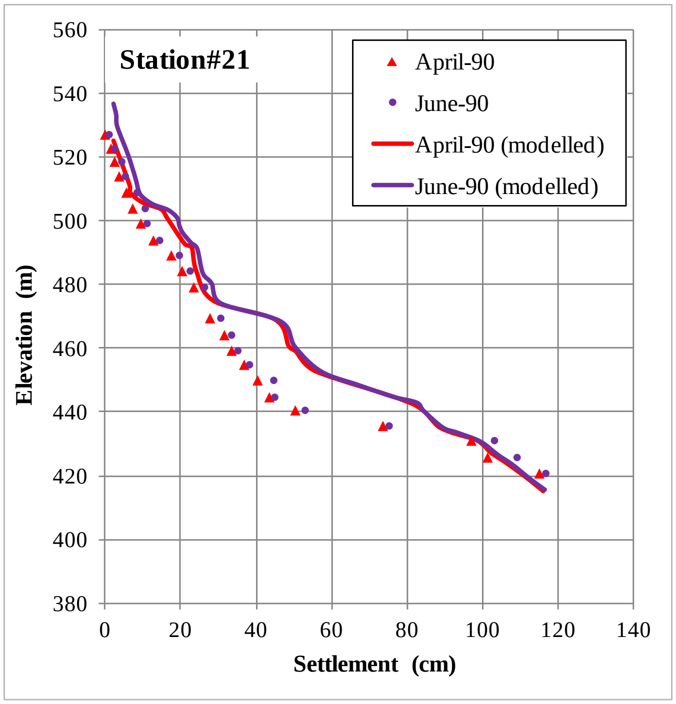

Fig.5. The observed and predicted settlements determined by back-calculation after reservoir filling at Station#21.

The settlements observed during the following years 1991 and 1992 can be modeled by using the same values for the consolidation parameters that was found by back-calculation of the settlements observed prior to the reservoir filling.

CONCLUSION

The settlement of the clay core of Atatürk Dam was studied based on laboratory tests and numerical analyses. The in-situ experimental measurements were adopted by back-calculation to model the recorded settlements in the clay core. Parametric studies and statistical analysis revealed that total settlements might reach almost 16m and the 70 % of total consolidation is expected to have been completed by March 1993.

The main issue of the case study was the unexpectedly large settlements observed at Elevation 440m which is almost 120m below the crest. Although the adopted consolidation parameters can well model the settlements observed prior to reservoir filling, the observed settlements that occurred during several months following the reservoir filling could not be modeled. It is very likely that the effect of water on the rock fill resulted in instability in the shelter and filter zones and which in turn caused a lateral spreading of the core material around and below Elevation 440m.

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