Long term behavior of staged construction of a dam on soft clay

La conduite à long terme du barage construit sur l'argile molle

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ABSTRACT
The staged-construction of Alibey Dam on the Alibey Creek near Istanbul in Turkey started in 1968 and ended in 1983 to generate a reservoir to meet up the water requirement of Istanbul. Alibey Dam had a geotechnical challenge of a 29.5 m high zoned earth-fill dam on 33-m-thick soft alluvial foundation and occasional sand bands. Alibey Dam consists of upstream cofferdam, downstream cofferdam, main body and test embankment. Before the construction of Alibey Dam, both extensive field and laboratory tests were performed to determine the engineering parameters of foundation soils. During the construction and approximately 30 years after the construction of the dam, the behavior of the foundation soils and the embankments were monitored using extensive instrumentation placed into the foundation soils and the dam body. All available performed and measured data before the construction, during the construction and approximately 30 years after the construction are collected and presented here to shed light on the staged construction of the dam on soft clay.

RÉSUMÉ
Afin de trouver une solution au problème de l'eau à İstanbul, on a commencé en 1968 à la construction du Barrage d'Ali Bey qui se trouve sur le ruisseau d'Ali Bey situé près d'Istanbul en Turquie et on l'a terminé en 1983. Ce barrage d'une hauteur de 29.50 m de remblais de sable est construit sur une fondation alluvialle de bande de sable ayant une profondeur de 33.00 m. Ce dernier est composé d'un batardeau en amont, d'un batardeau en aval, d'un tronc de base et d'un test de remblai. Les tests qui ont été fait sur les sols étendus et dans les labaratoires avant la construction du barage avaient pour objet la determination des paramètres du sol de fondation. Durant sa construction qui a duré approximativement trente ans, la mesure de la conduite de la fondation et du remblai se faisait avec des instruments de mesure placés sur le tronc et sur la fondation. On a évalué toutes les données enregistrées pendant 30 ans avant, pendant et après la construction du barrage et grâce à ces données on a pu présenter la conduite du barrage fondé sur l'argile molle.

Keywords: staged construction, earth fill, dam, soft soil, Turkey

1 INTRODUCTION

The design and construction of water structures such as dams is often different than the conventional civil engineering projects in terms of area of the construction of any kind of water supply. Dams are usually constructed on thick alluvial soils which hold soft and weak clays. Foundation treatment of a dam on soft clay always demonstrates a challenge to geotechnical engineers both to cope with stability problems and to minimize deformations and lateral displacements. Therefore, accurately determined properties of foundation soils under load of dam structures become critical design criteria.

Istanbul's water demand in 1960s forced Turkish geotechnical engineers to build the dam on an alluvial foundation and apply foundation treatment for the purpose of preventing the excessive settlement and the undesirable consequences. The present location of the Alibey Dam project has approximately 33-m-thick soft valley sediments which include clay deposits with occasional sand bands. Therefore, the staged construction was initiated in 1968 to control the excess pore water pressures, the rate of deformations and cope with stability problems using extensive instrumentation.

The available measured soil properties and the recorded settlement measurements of the Alibey Dam project are used here both to establish the correlations among soil properties and to shed light on the successful construction of staged construction of the Alibey Dam project.

2 DESCRIPTION OF THE PROJECT

Alibey Dam is located on the Alibey Creek at about 5 km north of the Golden Horn and is part of the water supply system for the city of Istanbul, Turkey. Due to economical and foundation problems, the 15-year-staged construction started in 1968 and ended in 1983 to generate a reservoir to meet up the water requirement of Istanbul. Alibey Dam consists of upstream cofferdam, downstream cofferdam, main body and test embankment. The dam has 29.5 m-height, an earth fill volume of $2x10^6$ m^3, reservoir volume of $35x10^6$ m^3, drainage area of 160 km^2 and reservoir capacity of 51 million m^3. The crest length of the dam is about 300 m. The general layout view and the cross-section view of the Alibey Dam project are presented in Fig. 1 and 2, respectively.

The behavior of foundation soils and the dam during construction and after long term construction were monitored with help of 120 piezometers, 26 settlement plates, 5 inclinometer stations, 6 total stress cells and 4 seismic instrumentations in order prevent the undesirable consequences. Some of the instrumentations are still in use to monitor the behavior of the dam under various load combinations.

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3 FIELD AND LABORATORY TESTS TO INVESTIGATE FOUNDATION

The way to have economical and safe structures in civil engineering projects always goes through extensive subsurface explorations and field tests supported with laboratory works. Therefore, the extensive subsurface investigations, the field tests and laboratory tests were conducted to characterize the foundation soils of the Alibey Dam project before the construction started. Approximately 1700-m-soil-boring at more than 49 locations supplemented with laboratory testing was carried out to define the nature of foundation strata and the engineering properties of foundation soils.

Allibey Dam was constructed on a 33-m-tick layer of alluvium overlaying a slightly weathered and a moderately permeable slate formation. These layer and thickness would be identified as (from top to bottom): 0-2.1-m-thick brown silty clay, 2.1-11-m-thick green clay, 11-25.3-m-thick blackish (dark) clay, 25.3-27-m-thick clay with sand and gravel, 27-27.78-m-thick sand and gravel with clay, and 27.78-30-m-thick bedrock.

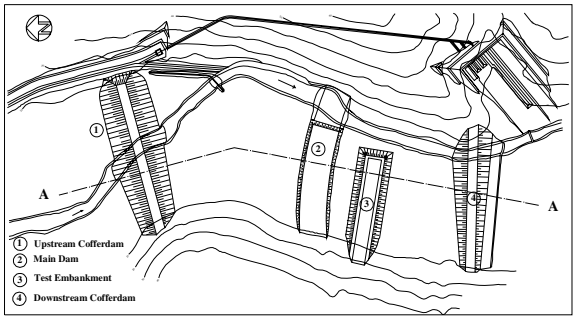

Figure 1. General layout view of the Alibey Dam project.

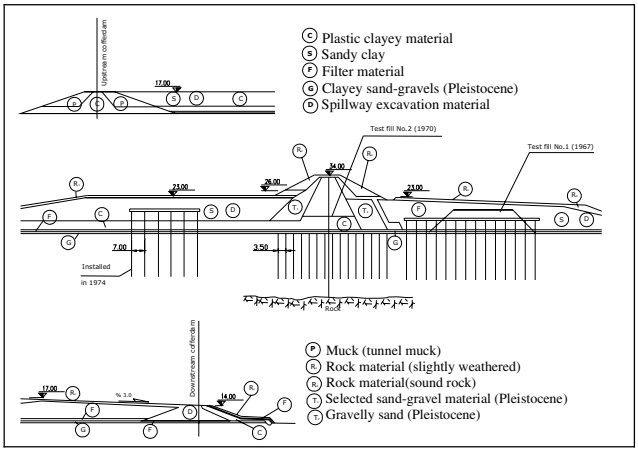

Figure 2. Cross-section view of Alibey Dam.

The samples along the foundation soils at dam site were taken to laboratory to determine natural water contents (W_n), liquid limits (LL), plastic limits (PL), plasticity indexes (PI), compression index (C_c) and preconsolidation pressures (σ'_p) of the foundation soils of the dam. The overall range of natural water content, liquid limit, plastic limit, plasticity index, compression index and preconsolidation pressures were as follows: 18-91 %, 20-90 %, 13-44 %, 3-67 %, 0.18-0.63 and 86-178 kPa, respectively.

The field vane shear tests were performed at fourteen locations of the dam site to determine the maximum undrained shear strength (S_{uo}) and remolded undrained shear strength (S_{uor}) of foundation soils. The overall range of undarined shear strength of foundation was 24-100 kPa and had almost uniform shear strength of 40 kPa. The sensitivity (S_t) of the foundation soils, calculated based on the ratio of S_{uo} to $S_{uor.}$, was around 4, which represents very sensitive clay condition. The soil profile, natural water content, liquid limit, plasticity index, maximum undrained shear strength and sensitivity of the foundation soils are presented in Fig. 3.

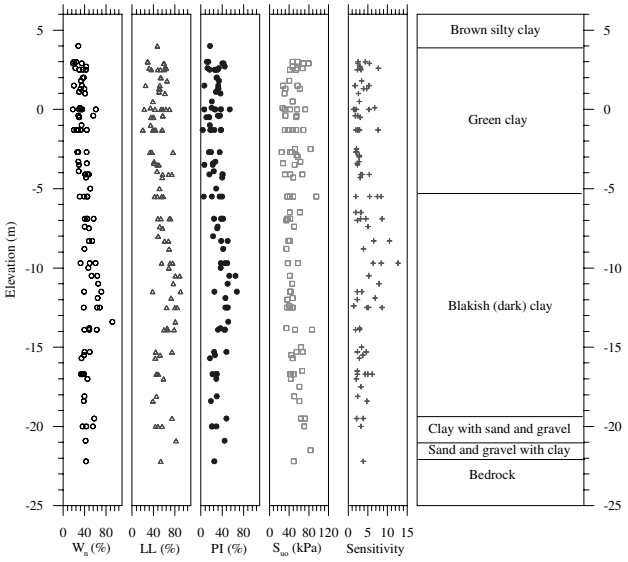

Figure 3. Measured natural water content (W_n), liquid limit (LL), plasticity index (PI), undarined shear strength (S_{uo}) from field vane test and sensitivity.

The main problem of the design and construction of dams on soft clay is excessive settlement under loads. The settlement analyses of the foundation soils of the Alibey Dam project were carried out using the simplified one-dimensional settlement methods available at the time of the project before the construction started. Therefore, the samples from different level of the foundation soils at the dam site were taken to laboratory to conduct one-dimensional odometer tests to determine the preconsolidation pressure (σ'_p) and compression index (C_c). The compression indexes and preconsolidation pressures, calculated with help of the void ratio (e_o)-effective stress curves, were used to predict the primary settlement of the foundation soils successfully.

The calculated compression indexes and the void ratios from the Alibey Dam project are plotted in Fig. 4 to establish the relation between C_c and e_o for only the case of Alibey Dam project as Skempton (1944), Rendon-Herrero (1983) and Nagaraj & Murty (1985) did in the past for the various clays. Almost a linear relation between C_c and e_o for the Alibey Dam project are found in Fig. 5 and would be expressed as:

$$C_c = 0.395e_o - 0.104 \quad (1)$$

The results of field vane shear tests at the dam site are also here evaluated to develop a correlation between plasticity index and the mobilized undrained shear strength for only the case of Alibey Dam project as Skempton (1957), Chandler (1988) did for their own cases. Bjerrum (1972, 1973) analyzed embankment, footing, and excavation failures in terms of in situ vane undrained shear strength ($S_{uo(FV)}$). Bjerrum (1973) recommended the in situ vane correction factor (μ) to find the mobilized undrained shear strength ($S_{uo(mob)}$) as follows:

$$S_{uo(mob)} = \mu S_{uo(FV)} \quad (2)$$

$$\mu = 1.7 - 0.54*\log(PI) \quad (3)$$

Either the ratio of $S_{uo(mob)} / \sigma'_p$ for over consolidated clay (OCC) or the ratio of $S_{uo(mob)} / \sigma'_{vo}$ for normally consolidated clay (NCC) versus plasticity index is plotted in Fig 5. The correlation for the Alibey Dam project between $S_{uo(mob)} / \sigma'_p$ or $S_{uo(mob)} / \sigma'_{vo}$ and plasticity index from the data fit line would be expressed as:

$$[S_{u(mob)}/\sigma'_p]_{OCC} \text{ or } [S_{u(mob)}/\sigma'_{vo}]_{NCC} = 0.179 + 0.687PI^{-0.5} \quad (4)$$

where σ'_{vo} is present effective overburden pressure.

Mesri (1975) showed that the mobilized shear strength for stability analysis can be expressed, independently of the plasticity index, as:

$$S_{uo(mob)} = 0.22\sigma'_p \quad (5)$$

$0.22\sigma'_p$ in Fig. 5 becomes the lower boundary for the mobilized undrained shear strength of foundation in the Alibey Dam project.

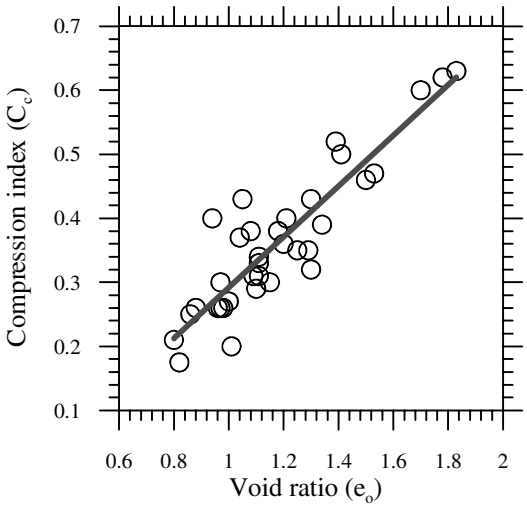

Figure 4. Measured compression index from odometer tests versus void ratio.

4 CONSTRUCTION

Alibey Dam was the fist dam in Turkey constructed on alluvial soil and also the first dam foundation treatment was applied for the purpose of preventing the excessive settlement and the undesirable consequences. The location of Alibey Dam has a 33-m-tick layer of alluvium overlaying a slightly weathered and a moderately permeable slate formation. After the evaluation of the foundation soils, two alternative construction options were considered. The first alternative was the removal of the alluvium and backfilling it with compacted impermeable soil. However, the concern of large quantities of water and stability of excavation were main problems to be handled in the first option. The staged construction, chosen due to necessity and speedy dissipation of pore water pressures and economical reasons, was initiated at February 1968 and ended at May 1983. The behavior of foundation soils and the dam during construction and after the long term construction were monitored with help of 161 instrumentations placed either into the foundation soils or the dam itself. Some of those instrumentations are still in use to monitor the behavior of the dam under various conditions.

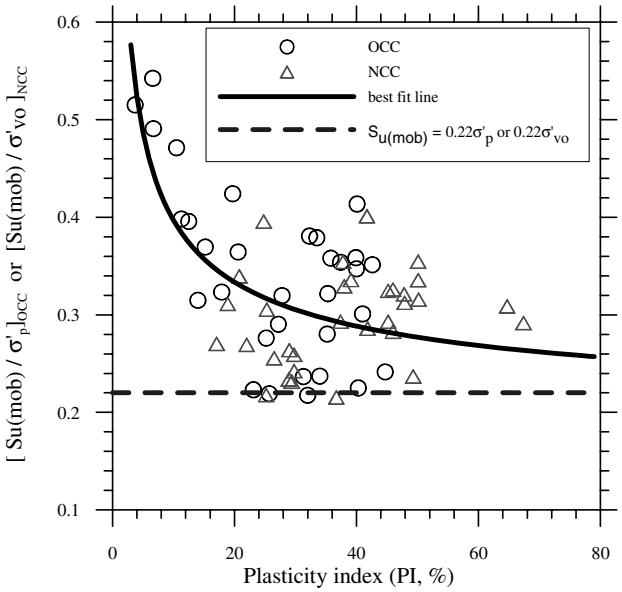

Figure 5. The mobilized undrained shear strength is normalized by either preconsolidation pressure for OCC or by effective overburden pressure for NCC versus plasticity index.

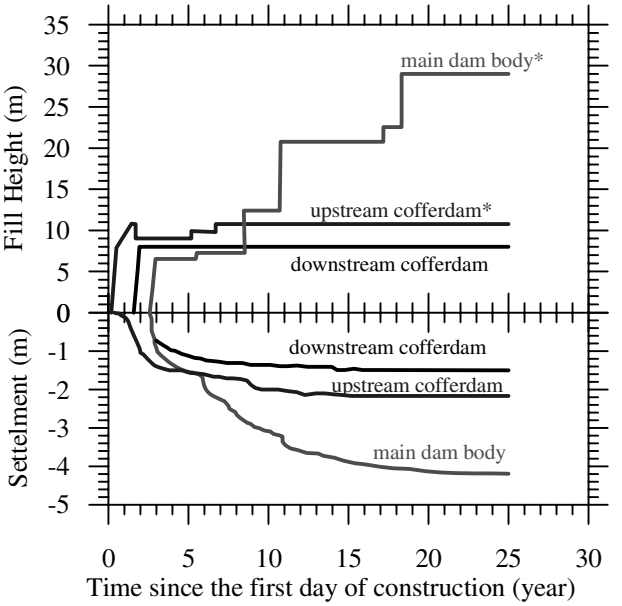

Figure 6. Construction program and recorded settlements of main dam, upstream cofferdam and downstream cofferdam (*some portion of fill height was taken from Ozcoban et.al (2007)).

The construction program and the recorded settlements of main dam, upstream cofferdam and downstream cofferdam are plotted in Fig. 6. In 1968 the construction of upstream cofferdam and following year the construction of downstream cofferdam had been initiated. Due to the high pore water measurements ranging between 73% and 98% and the settlement at the upstream cofferdam recorded as 99 cm, the construction was halted for one year in order to wait the dissipation of pore water pressure. After one year waiting period, recorded settlement of upstream cofferdam was 110 cm. 2 m fill was removed from upstream cofferdam in 1970 due to high pore water pressure. In some years only one or two meters of fill could be placed on the previous staged construction of dam due to high pore water pressures.

The consolidation settlement of soft clays takes long time to complete. To shorten the consolidation time, vertical drains are usually installed together with preloading by embankment. Thus, the water, which is squeezed out during consolidation of clay due to the hydraulic gradients created by the preloading, can flow in horizontal direction toward to vertical drains. The use of vertical drains reduces the drainage path and allows the clay to gain the strength to carry the new loads by its own.

After the evaluation of the excess water pressures and the foundation settlement measurements at the Alibey Dam project, the sand drains at main dam and both sides of the main dam in Fig. 2, having spacing of 3.5 m to 7 m and depth of up to 20 m, were installed to accelerate the dissipation of water pressure and increase the shear strength of foundation soils. After completion of sand drain, it was observed that the rate of dissipation of excess pore water was faster with sand drain.

The excess pore water measurements in a foundation under loads are generally evaluated to determine consolidation progress and to have next stage construction of fill. The degree of consolidation at a distance z at any time t is evaluated as:

$$U_z = 1 - (u_z / u_o) \quad (6)$$

where u_z is excess pore water pressure at time t and u_o is initial excess pore water pressure.

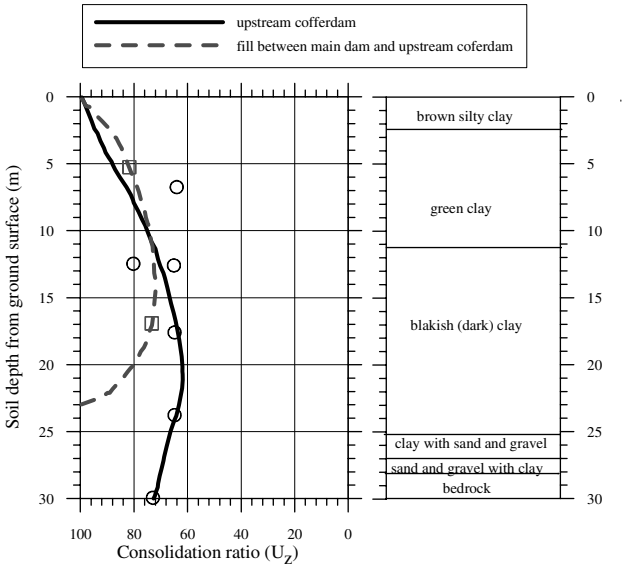

Figure 7. Example of consolidation curves from piezometric measurements.

Hence, the degree of consolidation curves at 64th month of initiation of construction of upstream cofferdam and at 58th month of initiation of construction of fill between main dam and upstream cofferdam were presented in Fig. 7 as a sample of the many consolidation curves of the Alibey Dam project. Each stage of construction of Alibey Dam was decided on the consolidation ratios and the recorded settlement measurements such as presented in Fig. 6 and Fig. 7.

The dam was completed in 1983 successfully and the recorded maximum settlements were 4.41, 2.26 and 1.58 m for main dam, upstream cofferdam and downstream cofferdam, respectively.

5 CONCLUSIONS

Alibey Dam was the first dam in Turkey constructed on soft soil and applied foundation treatment methods such as sand drains, staged construction method. This project showed that subsurface exploration, proper field testing supported with accurate laboratory tests, appropriate instrumentation, careful monitoring of the collected data and the evaluation of monitored data are vital prerequisites for a successful and economical design of construction of a dam on soft clay. The Alibey Dam project was completed without any failure and serves still its design purposes due to all compulsory works done before construction started.

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