Determination of deformations in soft soils with a coupled analysis-Alibey Dam

Détérmination des déformations dans les sol mous par les analyses accouplés-Barrage Alibey

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ABSTRACT: In this paper, the results of a coupled analysis using the finite element method, which has been performed to investigate the stress-strain-consolidation behaviour of a dam foundation, are presented. The stress increases in the foundation soil layers due to loading of the embankments during the staged construction and the corresponding pore pressure increases and displacements have been computed. The stress increases and the immediate deformations were calculated using an elasto-plastic analysis taking into account the consolidation behaviour. In the numerical analyses, a computer code named PLAXIS was used and the calculated time-dependent settlements, lateral displacements and the pore pressures compared well with the measured values.

RÉSUMÉ: Dans cet étude, le resultat d'un analyse accouplé utilisant le méthode des éléments finis, utilize pour étudier la constraint-deformation-consolidation d'une fondation de barrage est présénté. La tension augmente dans les couches de fondation a cause des charges des talus durant la construction, et l' augmentation de la pression correspondant du pore et les deplacements a été calculés. L' élevation du tension et les déformations immediates ont été calculés par des analyses elasto-plastiques et la conduite consolidant a été aussi tenue compte. Dans les analyses numériques, un ordinateur programme, surnommé PLAXIS a été utilisé et les déplacements laterales, et les pression porales ont étés comparés avec les valeurs mesurées.

1 INTRODUCTION

In recent years, as a result of the developments in numerical analyses and computer technology, it became possible to perform more realistic stress-strain-consolidation analysis of the behaviour of embankments constructed on soft soil deposits. Several researchers have published the results of such analyses. In this study, the deformation behaviour of the foundation of Alibey Dam was investigated for both during construction and after construction conditions.

Alibey Dam was built as an earth fill dam on soft alluvial deposits to meet the water requirements of the city of Istanbul. The behavior of foundation layers supporting the dam built by the staged construction method was investigated with a coupled analysis and the computed values were compared with the measured values. In the numerical analysis a computer code named Plaxis was utilized, and while the stress increases and immediate deformations were computed with an elasto-plastic analysis, the consolidation settlements and dissipation of excess pore pressures were computed with a consolidation analysis based on Biot's theory. The findings of this investigation provide a greater insight regarding construction of embankments on soft soil deposits similar to Alibey Dam.

2 DAM AND FOUNDATION STRATIGRAPHY

2.1 Dam characteristics

The construction of Alibey Dam started in 1968 as an earth fill reservoir to meet the water requirements of the increasing population and rapid industrialisation of Istanbul. The dam, planned to be finished in 15 years by the staged construction method, is located in a valley. The 33-m thick valley sediments comprised of several medium stiff clay layers with occasional sand bands, the consistency of which increases with depth. The dam have the following dimensions: the crest width 15 m, the height 28 m, the base width 304 m, and the length 550 m. Alibey Dam consists of an inlet and outlet cofferdam, main body, and the internal embankments. The cross-section of the dam and the stratigraphy are shown in Figure 1.

The dam, with an earthfill volume of approximately 2 million cubic meters, contains a typical clay core together with gravelly and sandy filter materials and a rock fill at the top. In the preliminary planning studies, two construction alternatives were considered, one being the staged construction on the existing clay layers and the other being the excavation of the clay layers and construction of the dam on the bedrock. It was decided that the first alternative was more economical. Due to the extraordinary cross-section and the availability of long-term monitoring data, Alibey Dam provides an interesting case history for geotechnical engineers.

During the construction of the earthfill embankments an extensive field measurement and monitoring scheme was planned in order to provide safety against undrained failure of the foundation and to keep the displacements under control. A great number of settlements plates, piezometers and inclinometers were placed in the foundation soil, and the behavior of the foundation soil under applied loads has been carefully observed. Because of the extensive instrumentation and monitoring that continued even after the completion of the reservoir, valuable data have been collected for describing the long-term behavior (over a period of 25 years) of the alluvium soil on which the dam was constructed. Additionally, a geodesic network system was established in 26 different points on Alibey Dam and its vicinity in March, 1987 and measurements have been made periodically. The soft soil deposits supporting Alibey Dam have been subjected to different levels of loading at five different cross-sections of the dam and consolidated under different drainage conditions including sections with fully or partially penetrating vertical drains. In order to study the behavior of this alluvial deposit, which is expected to have similar initial conditions at different dam sections, a series of field and laboratory investigations were carried out, the results of which were utilized in obtaining the geotechnical parameters needed for the numerical analysis.

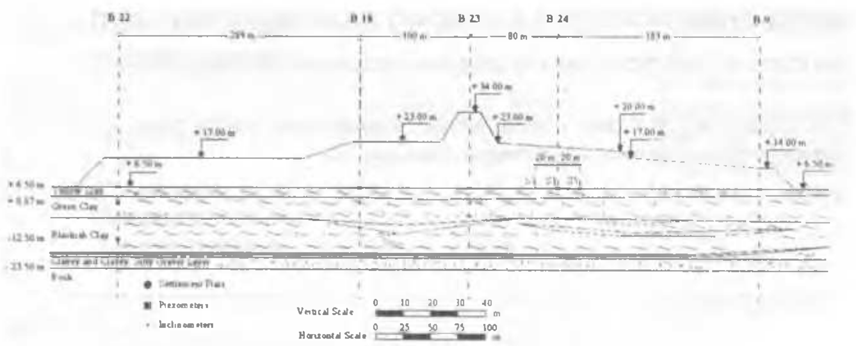

Figure 1. The cross section of the dam and the foundation layers.

2.2 *Construction program and field instrumentation*

The embankment for Alibey Dam was constructed in 15 years by staged fill placement in order to avoid stability problems and to minimize the problems, which would arise from the large settlements expected to occur. The earth fill construction had started at elevation +6.50 m and the fill height reached elevation +17.0 m at section B22 (upstream embankment), +23.0 m at B18 (intermediate fill), +34.0 m at B23 (crest), +21.50 m at B24 (intermediate fill) and +14.0 m at B9 (downstream embankment). The staged construction program of the dam is shown in, Figure 2.

The field instrumentation placed in the foundation layers included:

- A total of 21 settlement plates placed at the original ground surface underlying the dam embankment
- Four different types of piezometers placed at various depths to measure the pore pressure build up.
- Five inclinometers reaching the bedrock level placed underneath the crest to monitor the lateral displacements in north-south (N-S) and east-west (E-W) directions. Inclinometer readings were collected for the first six years of the embankment construction, after which inclinometers were damaged and no readings could be taken.
- Concrete blocks established on and around the dam after the embankment construction was completed in March 1987 for geodesic measurements and for placing seismographs to measure surface movements after the completion of the dam.

The location of field instrumentation is shown in Figure 1.

2.3 *The geotechnical characteristics of foundation soils*

The alluvial layers underlying Alibey Dam had a thickness of up to 33 m and four main strata could be identified down to the bedrock. These layers are identified as (from top to bottom) yellowish clay, greenish clay, greyish black clay and clayey-sandy gravel. Within cohesive layers several sandy-gravelly pockets were encountered (Özaydın, et al. 1998). A summary of the geotechnical properties of the subsoils at the dam site obtained from both field and laboratory tests are shown in Table 1.

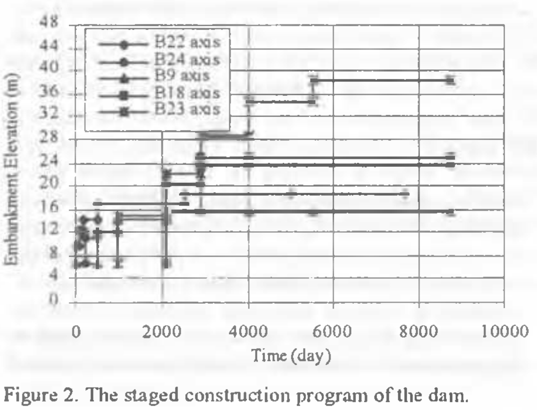

Figure 2. The staged construction program of the dam.

Table 1. Subsoil geotechnical properties of the dam site

Soil Properties	Yellow Clay	Green Clay	Black Clay
Thickness of soil layer (m)	1-3.6	6-11	10-14
Liquid limit (%)	20-40	40-60	55-70
Plastic limit (%)	15-35	15-40	15-40
Moisture content (%)	20-40	25-40	40-60
Saturated unit weight (kNm^3)	20	19	17
Over consolidation ratio	4-8	1-3	1-2
Undrained shear strength (kPa)	-	30-80	25-75
Modified compression index (λ^*)	0.05	0.12	0.13
Modified swelling index (κ^*)	0.01	0.023	0.025
Permeability change index (C_k)	0.263	0.507	0.717
Angle of internal friction (^{0})	20	18	17
Specific gravity of solids	-	2.70	2.72

3 PREVIOUS INVESTIGATIONS (RESEARCH WORK)

Several researchers investigated the behavior of the foundation of Alibey Dam during and after the embankment construction. (Soydemir 1970, Mercangöz 1996, Özçoban 1997, Kılıç 2000). The findings of these researchers who employed different methods of analyses are summarized below.

Soydemir (1970) was involved with the project at the early stages of construction. He studied the immediate settlements of the soil layers underneath the upstream embankment using the finite element method with an elasto-plastic analysis and the consolidation behavior with the one-dimensional consolidation theory of Terzaghi. Similar analyses were performed long after the completion of the dam construction to study the behavior of soil layers under different sections of the dam subjected to different levels of embankment loading, involving different drainage conditions by Mercangöz (1996), Özçoban (1997) and Özaydın et al. (1998). In these investigations, the stresses and deformations developed in the foundation layers underlying the dam during the staged construction of the embankment were computed using a finite element computer code named ANSYS utilizing elasto-plastic analysis. In the analysis, the improvement in soil properties as a result of consolidation at different stages during construction was taken into account. The consolidation behavior was analyzed separately utilizing the stress increases computed from the finite element analysis and using the one-dimensional Terzaghi consolidation theory. The computed settlement values were compared with the field settlements recorded from the start of the construction in 1968 to 1991.

The results of the above analyses have shown that the construction of the dam embankment to its final elevation on the foundation layers at their initial in-situ properties would have led to excessive deformations resulting from wide spread plastic flow at the base of the dam. It was also shown that if the improvement in soil properties due to consolidation of the soil layers during the staged construction is taken into account in the analysis, the deformations resulting from plastic flow of foundation layers is limited. Because of the fact that this phenomenon was taken into account in the earth fill construction program, the construction of the dam was safely completed. The results of these analyses have also shown that even under rather low levels of loading plastic regions would develop in limited areas and an elasto-plastic analysis is needed for the analysis of the behavior of earth structures built on similar soft soil conditions. By taking into account the improvement in soil properties due to consolidation, it is observed that the computed vertical and lateral displacements are reduced considerably.

With respect to settlement-time behavior, the choice of representative values of the coefficient of consolidation for the soil layers in the field is the critical parameter in the analysis. It was observed that coefficient of consolidation values valid for the field conditions were much larger than the values predicted from the laboratory test results. The values estimated by back-calculation from the field pore pressure and settlement measurements have led to a much more realistic prediction of the field behavior.

In view of the expected presence of sand pockets and bands in the alluvial deposits, the unreliability of the laboratory results was not surprising. The Asoaka (1978) method, which utilizes the field settlement measurements for prediction of the coefficient of consolidation, proved to give quite satisfactory results. In the analysis, in accordance with the construction program, first the settlements under the upstream embankment were computed and compared with the field measurements, then the settlements under the other sections of the dam subjected to surcharge loading due to the staged construction were computed and compared with the settlements recorded for a period of 25 years. The results of the above analyses have shown that Terzaghi's one-dimensional consolidation theory could predict the field settlements quite satisfactorily provided that the improvement in soil properties during staged construction is taken into account. Consequently, a sufficient level of safety against bearing capacity failure is sustained and plastic deformations are limited.

The material properties for the foundation layers of Alibey Dam as determined from the field and laboratory investigations carried out during a period extending from 1966 (preconstruction) to 1996 (this research) are given in detail by Kılıç and Yıldırım (2000).

4 COUPLED ANALYSIS FINITE ELEMENT MODEL

In order to carry out a more advanced analysis of the behavior of the foundation of Alibey Dam taking into account the coupled nature of stress-strain-consolidation behavior, a finite-element computer code named Plaxis 7 (1998) was utilized. The main features of the finite element model are summarized below.

- The rather unusual dam section and foundation layers are shown in Figure 1. Because the upstream embankment is quite far away from the main dam, and it was built before the others, it was numerically modelled separately and the results were compared with the field measurements to verify the geotechnical parameters used in the analysis.
- The finite element mesh for the upstream embankment extended 200 m in the longitudinal direction, and the finite element mesh for the rest of the dam (excluding the upstream embankment) extended 593 m. The finite element mesh for the upstream embankment consisted of 489 triangular elements with 15 nodal points for each element with a total of 4063 nodal points and 5868 stress points. The finite element mesh for the main dam consisted of 958 triangular elements with 15 nodal points for each element with a total of 7885 nodal points and 11495 stress points. The upstream embankment and the neigbouring fill was built in 6 stages and the rest of the dam in 7 stages and this was taken into account in the numerical modelling. The finite element model combined both the embankments and the foundation layers. The staged fill construction is modelled by adding fill elements to the finite element mesh.
- The soft alluvial layers are underlain by 3.5-5.0m thick clayey-sandy gravel layer which is followed by the bedrock (assumed to be rigid and impermeable).
- For the analysis of the behavior of the cohesive layers, Modified Cam Clay model (MCC) (Roscoe and Burland 1968) was used. This model is frequently used for the analysis of geotechnical problems in which the stress increments are analysed as effective stresses. The model includes an isotropic flow function, non associated flow rule and a hardening law independent of plastic strain gradient, and incremental elasto-plastic stress-strain formulation. In this investigation, the failure was modelled with Mohr-Coulomb failure criterion which is identified as "Soft-Soil Model" in the Plaxis code. For the analysis of the behavior of cohesionless layers and highly overconsolidated cohesive layers "Hard-Soil Model", which is similar to the hyperbolic model (Duncan and Chang 1970) but adopted to plasticity theory, wass used. The dilatational effects were taken into account and the flow condition was defined with a flow cap.
- In the analysis, the horizontal and vertical coefficients of permeability of the clay layers were taken as 0.005 m/day and 0.002 m/day, respectively. The change in the coefficient of permeability with the consolidation pressure was modeled with a c_k coefficient. As a result of the parametric studies, the ratio of the horizontal to vertical coefficient of permeability was determined to be 4. In the analysis, the cohesive layers were assumed to behave as undrained, the clayey-sandy gravel base layer, the sand bands and the vertical sand drains were assumed to behave as drained. The granular embankment fill material was assumed to behave linearly elastic. Because no samples could be collected from the embankment fill, the sand bands and the clayey-sandy gravel layer, their geotechnical properties could not be determined by laboratory tests. For the embankment fill, the drained elastic modulus was chosen as 8000 kPa, Poisson ratio as 0.40 and unit weight as 20 kN/m^3. The behavior of the sand bands and the clayey-sandy gravel layer were modelled with Hard-Soil Model and for the initial stress conditions their material properties were estimated from the standard penetration and pressuremeter tests (Kılıç and Yıldırım, 2000).

5 STRESS-STRAIN AND CONSOLIDATION ANALYSIS RESULTS

The stress-strain-consolidation behavior of the foundation of Alibey Dam subjected to staged loading was analysed with an instantaneous ioading (undrained) analysis and a consolidation (drained) analysis under sustained loading taking into account the consolidation periods in accordance with the construction program. The results of the analyses are presented for the five different section of the dam involving different fill heights and drainage conditions (sections B22, B18, B23, B24 and B9 as shown in Figure 1). The computed and recorded settlements are shown in Figure 3 and it is observed that they are quite comparable. The final surcharge loads at sections B22, B18, B23, B24 and B9 were 245, 370, 640 and 182 kPa, respectively. The recorded variation of settlements with applied surcharge loading and consolidation period in the field are predicted quite satisfactorily with the coupled analysis.

The variation of excess pore pressure with depth as computed by the consolidation analysis under different dam sections at various stages of loading indicate a double-drained condition towards the surface and the clayey-sandy gravel layer at the base overlying the bedrock. This behavior is consistent with the findings of Soydemir (1970), Mercangöz (1996), and Özçoban (1997). The pore water pressure recorded by piezometers under sections B22 and B24 are also observed to be comparable with

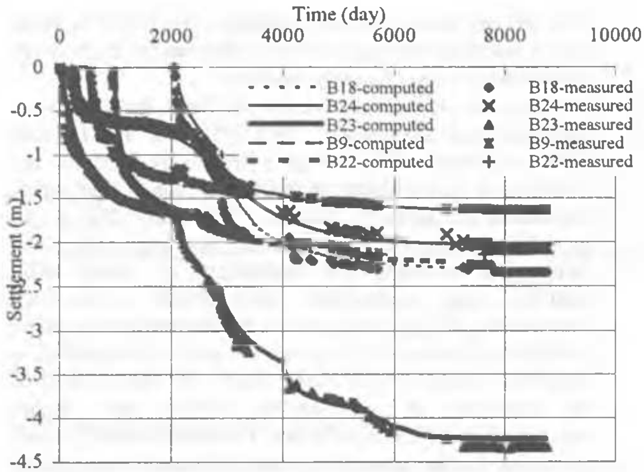

Figure 3 Computed and measured settlements in section of B22, B18, B23, B24 and B9.

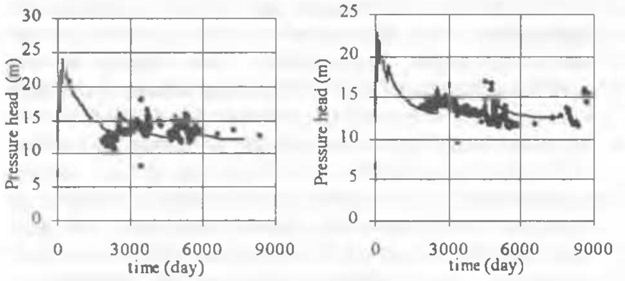

Figure 4 The measured and computed pressure head underneath B22 section at BH-1(-12.50 m).

the computed values. The recorded and computed pore water pressures underneath the upstream embankment (B22) at −12.50 m elevation and +0.67 m elevation are shown in Figure 4. The recorded values and computed values are shown as symbol and line, respectively. Again the predictions are quite successful.

The lateral displacements computed by the coupled analysis are observed to be smaller than the recorded values in the field (Özaydın, et al., 1998). In addition to inclinometers, geodesic measurements were made to monitor the surface displacements in three dimensions on the dam embankment. Comparison of these recordings with the computed values are given by Özaydın, et al. (1998). Geodesic measurements recorded between the years of 1987-1996 have shown that there are still small movements that the dam and other fills are undergoing.

The results the analysis have shown that the strength and stifness properties of the embankment materials and the sand bands did not effect the results very much, however, the difficulty in assessing the permeability characteristics of the clayey-sandy gravel base layer posed serious difficulties. Both the results of the analysis and the field observations have shown that the assumption of double drainage is valid as indicated in the previous research (Soydemir,1970 and Ozaydin et.al.,1996).

6 CONCLUSIONS

From the findings of this investigation of the analysis of the behavior of an earth embankment constructed on alluvial layers of low bearing capacity and high compressibility, the following conclusions are reached.

1. The accurate prediction of the behavior of soft and thick soil layers subjected to staged construction as in the case of Alibey Dam is very important for planning of the construction as well as the expected behavior after construction. The estimation of stress increases and soil deformations as realistically as possible is vital for the design and construction of earth fill structures on such soil deposits.
2. Field instrumentation and monitoring of displacements and pore pressure built up in the foundation layers are very useful in understanding the soil behavior and checking the validity of soil properties used in the analysis.
3. In the numerical analysis performed to predicte the soil behavior, rather realistic estimates of stress and displacements were obtained under staged loading. Field behavior can be predicted quite satisfactorily by considering plane stress conditions and elasto-plastic material behavior, and by performing undrained analysis for instantaneous loading and drained analysis for consolidation phases,
4. In the consolidation analysis, the anisotropic nature of the field permeability characteristics should be taken into account. The laboratory determined values of coefficient of consolidation are found to be not reliable and much more realistic estimates can be made by back calculation from the observed field behavior.
5. Use of Modified Cam Clay model seems to give results that are more comparable to the observed soil behavior than the use of traditional Mohr-Coulomb model .
6. The computed values of pore water pressures and the values measured in the field with piezometers did not compare as well as the settlements and this is partly attributed to the variation of water level in the reservoir and erratic nature of the field measurements.
7. In staged construction of earth embankments on soft and saturated soil layers, the monitoring of pore water pressure build up is very important and a realistic estimation of pore water pressures with the aid of coupled stress-strain-consolidation analysis is very useful.

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REFERENCES

Asaoka, A. 1978. Observational procedure of settlement prediction. *Soils and Foundations*, 18 (.4): 87-101.

Duncan, J. M. & Chang, C. Y. 1970. Non-linear analysis of stress and strain in soils. *Journal of Soil Mech. Foundation Div. ASCE*, 96 (SM5): 1629-1653.

Kılıç, H. 2000. *Yumuşak zeminler üzerine oturan dolgu barajlarda deformasyonların nümerik ve deneysel yöntemlerle belirlenmesi.* Doktora Tezi, YTÜ., Fen Bilimleri Enstitüsü, İstanbul.

Kılıç, H. & Yıldırım, S. 2000. Alibey Barajı temel zemini parametrelerinin belirlenmesi. *Zemin Mekaniği ve Temel Mühendisliği 8. Ulusal Kongresi*, İstanbul.

Mercangöz, B.B. 1996. *Yumuşak kohezyonlu zeminlerin kademeli yükleme altında davranışının nümerik analizi.* Yüksek Lisans Tezi, YTÜ., Fen Bilimleri Enstitüsü, İstanbul.

Plaxis 7. 1998. *Finite Element Code for Soil and Rock Analyses*, User Manual.

Roscoe, K. H. & Burland, J. B. 1968. On the generalized stress-strain behaviour of wet clay. *Engineering Plasticity*, J. Heyman and F.A.Leckie, eds., Cambridge University Press; Cambridge, England.

Soydemir, Ç. 1970. Alibey toprak barajı menba batardosu oturma ve stabilite etüdü. *İnşaat Mühendisleri Odası Türkiye İnşaat Mühendisliği V. Teknik Kongresi*, Ankara.

Özaydın, K., Yıldırım, S., Uzel, T., Özçoban, M. Ş., Berilgen, M. M., Hoşbaş, G. & Kılıç, H., 1998. *Yumuşak Zeminlere Oturan Dolguların Davranışı.* DPT Araştırma Projesi, İstanbul.

Özçoban, M. Ş. 1997. *Yumuşak zeminlere oturan dolgu barajların analizi.* Doktora Tezi, YTÜ., Fen Bilimleri Enstitüsü, İstanbul.