HORIZONTAL DEFLECTION ANALYSIS OF A LARGE EARTHEN DAM BY MEANS OF GEODETIC AND GEOTECHNICAL METHODS

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Abstract: Earthfill dams are subject to external loads that induce deformations to the structure and the foundations. The self-weight of a dam and the reservoir water pressure are primarily responsible for the increase of stresses within the dam body, which in time result in horizontal and vertical displacements, mostly of a permanent character. In this gradually evolving process, the dam geometry characteristics, the type of materials and their geotechnical properties play a key role in the geometrical changes in concern. Current techniques which are used to study the dynamic behavior of dams are based on statistical analysis of recorded displacements, as well as on predicted deformations derived from numerical modeling of physical parameters, such as external loads and construction element features.

The paper compares actually measured horizontal deformations resulted from a continuous geodetic monitoring record of the dam behaviour with a numerical back analysis. The geodetic data originate from a continuous, long-standing (> 25 years) monitoring program of the dam and the surrounding area. The geotechnical modelling of the dam is implemented using *Z_Soil*® software, which adheres to the finite element method. Numerical simulation was carried out in two-dimensional plane-strain conditions. The computed stresses and displacements refer to certain stages (construction, filling and operation) in the lifetime of the dam, whereas, in this study, emphasis is given on horizontal displacements. Comparisons of the computed deformations from the FEM analysis with those obtained from the geodetic monitoring record for a large number of control points established on the dam body revealed a very good agreement. These findings are of great importance considering that in the long-standing history of the dam different monitoring techniques (terrestrial and satellite) were implemented, the observation schemes varied and a large number of observers were involved.

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1. INTRODUCTION

Safety is the primary and most important reason for monitoring the deformations of dams. A secondary reason is the need for improving our knowledge of the mechanical behavior of dam embankments. Such knowledge enhances our understanding of the basic design concepts, which gradually leads to more effective constructions. Nevertheless, the benefits of a deformation monitoring process are further exploited if coupled with the results obtained by the numerical modeling of the mechanical behavior of a dam. In most cases of practical interest numerical modeling takes the form of a Finite Element (FE) model (Clough, 1960; Zienkiewicz et al 2005). In such a model, the physical continuous domain of a complex structure is discretized into small components called finite elements. Today, the FE method is extensively used in a wide number of applications as it can produce a reliable representation of a structure and its mechanical behavior.

In dam monitoring, the adoption of such an integrated approach has assisted in verifying critical design parameters for existing dams and for improving the design concepts of new structures (Szostak-Chrzanowski et al, 2001; Szostak-Chrzanowski et al, 2006; Guler et al, 2006). However, since no two dams are identical (in terms of material type, geometry, location characteristics, etc.), and the deformation monitoring data (observation types, length and quality of the deformation monitoring record, etc.) can vary considerably from one case to another, the findings of new studies can prove very useful in populating and standardizing this information to the benefit of the dam design and construction community.

This paper studies the mechanical behavior of the Mornos dam in Greece on the basis of a geodetic monitoring network and a FE model. More specifically, this study is confined in the detailed analysis and discussion pertaining to surface horizontal displacements and their modeling. A detailed analysis of the dam settlement is given in Gikas and Sakellariou (2008). Overall, the cross-examination of the deformation monitoring and the FE analyses suggest that the structure retains fully its structural integrity.

Figure 1: View of Mornos dam facing from downstream

2. GENERAL DESCRIPTION OF THE MORNOS EARTHEN DAM

Mornos dam is a large earth dam with a medium size central clay core. It is located about 220 km north-west of Athens, Greece. It is 126 m high, the crest length is 815 m and its width from toe to toe is 660 m (Figure 1). After construction of the cofferdams and diversion of the river, placement of impervious core material started in 1972. The dam was topped out in early 1977 and river closure was effected 1979. The first filling of the reservoir was completed in mid 1981. The river at the site and most of the reservoir area are situated on flysh formations. The embankment component aggregates, which vary in size from sand particles to gravels, consist mainly of sedimentary (limestone, sandstone and shale) rocks (Lahmeyer, 1976).

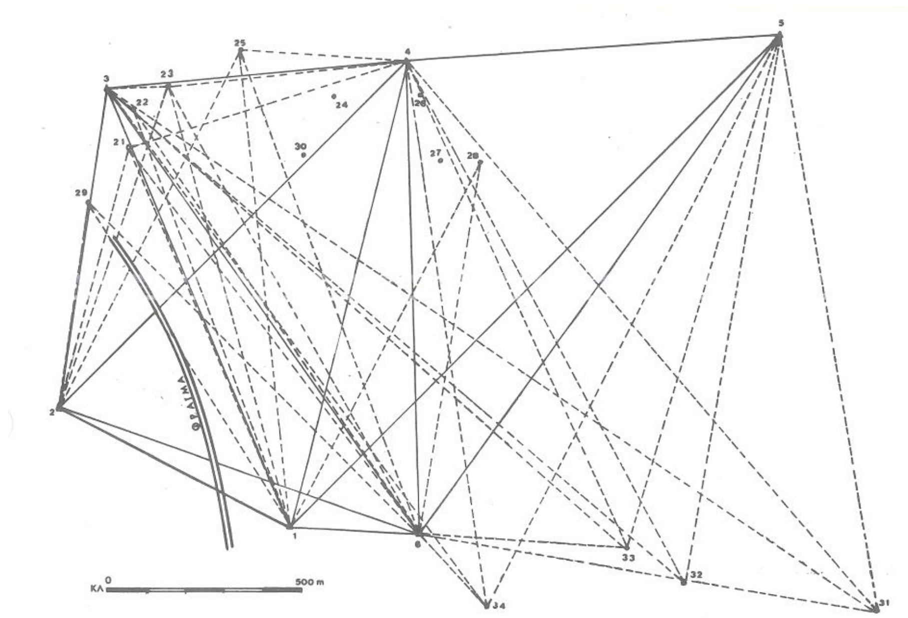

Figure 2: Dam site and geodetic network

3. SURFACE MOVEMENT MONITORING SYSTEM

3.1. Horizontal Control Networks and Instrumentation

The deformation monitoring system of the dam comprises various types of instruments (piezometers, magnetic extensometers, accelerometers, etc.). The geodetic monitoring system consists of two principal geodetic control networks. The main network was established in early 1976 for monitoring the greater area and the embankments of the dam. It consists of 15 reference stations, the locations of which were specified by geologists and civil engineers (Mitsakaki and Stathas, 1983). As shown in Figure 2, the length of the sides of the network varies between 0.3 km and 2.5 km. A more dense geodetic control network was established along the crest of the dam, on the downstream face and the abutments. In total, 53 control stations were established to monitor the deformation of the dam body (Figure 3).

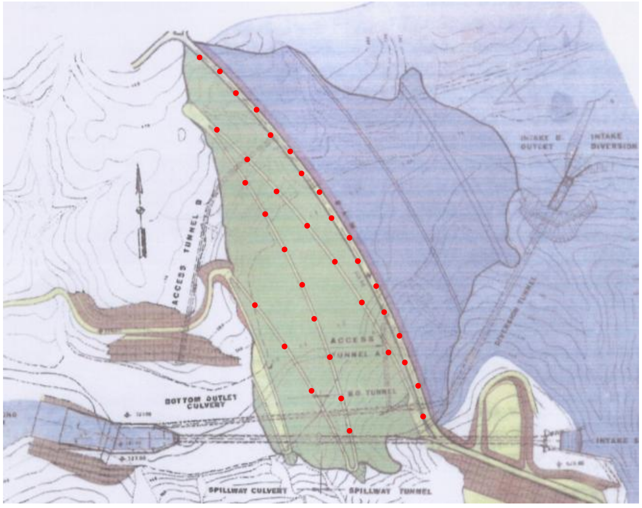

Figure 3: Geodetic control points at the crest and downstream abutment

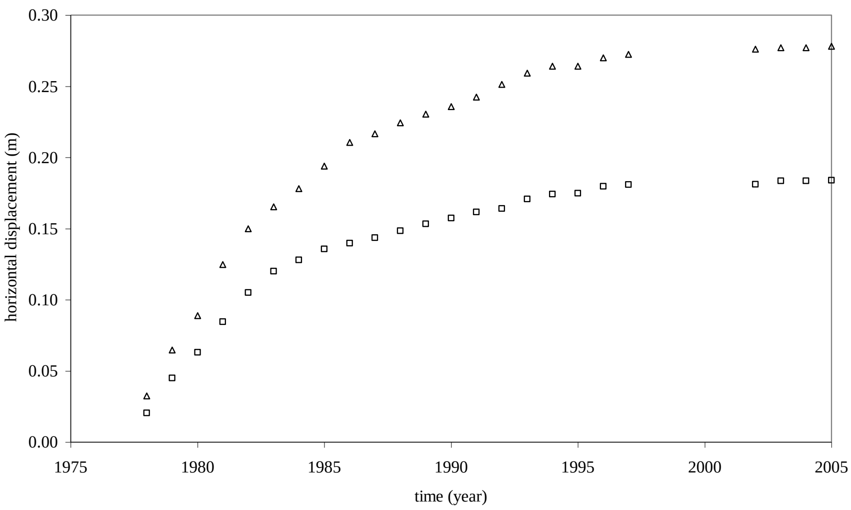

Figure 4: Accumulated horizontal displacements at control stations S21 (at the middle) and S32 (near the tail-end) of the dam

3.2. Available Data and Horizontal Movements

Since 1976 till today a number of observation techniques and a mixture of geodetic instruments have been used for monitoring the deformations of the dam and the abutments. Initially, a DKM-3A theodolite (0″.5) and an AGA-Model 8 EDM (±5mm ±1 ppm) were used (Agatza-Balodimou and Mitsakaki, 1985), which soon after gave place to modern total stations, whereas in more recent years satellite (GPS) methods were employed (Gikas et al, 2005). During the stage of first filling of the reservoir (1979 - 1981) and in the first years of operation geodetic measurements were repeated every four to six months, whereas more recently major geodetic campaigns are undertaken on an annual basis.

Analysis of the deformation monitoring data at the control points of the main geodetic network reveals that the horizontal displacements are statistically significant - howbeit, they exhibit rather small velocity vectors (~2 mm/year). On the contrary, the horizontal deflections observed at the crest of the dam result in much larger movements, which are aligned on the upstream-downstream direction. Figure 4 shows the progression of horizontal displacements of control points S21 and S32, which are located at the middle and towards the tail-end of the crest. From this plot it is evident that maximum displacements occured rapidly during the post-construction period of the dam with a tendency of stabilization in more recent years.

4. NUMERICAL MODELING OF DEFORMATIONS

For the purpose of this work, three fundamental FE models were adopted (Karanasiou, 2007; Agelopoulou, 2007). These models correspond to the main stages in the lifetime of the dam (i.e., construction, first filling and operation). The FE analyses assume two-dimensional plane-strain conditions. A relatively fine mesh consisting of approximately 4000 nodes was constructed to model each of a total of eleven equally spaced cross-sections along the crest of the dam using *Z_Soil*® software (*Z_Soil* , 2003; Figure 5).

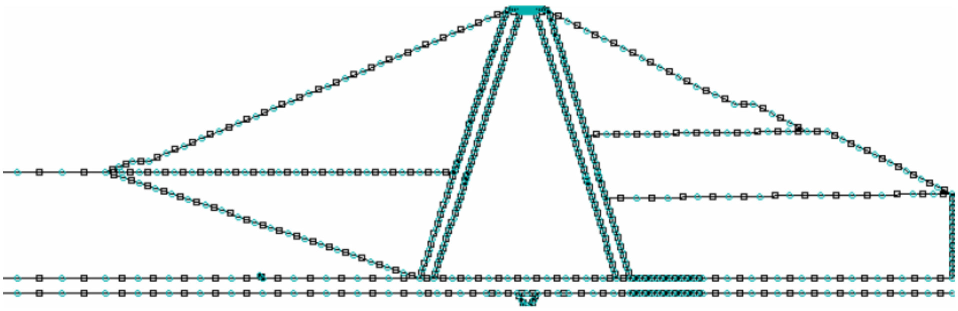

Figure 5: Construction of FE mesh

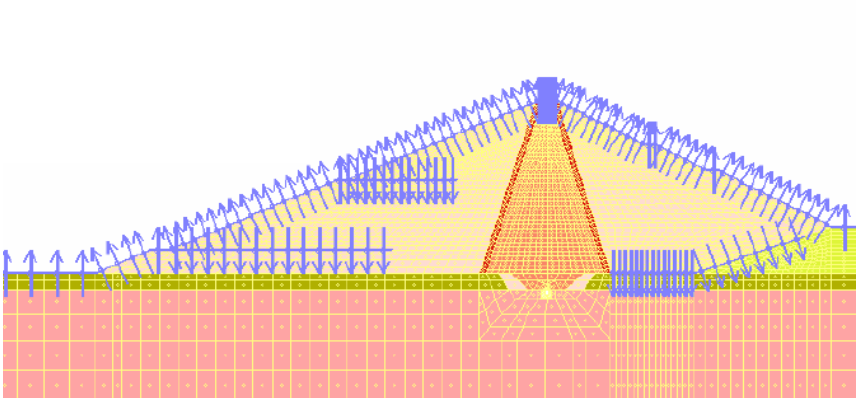

Figure 6: Modeling of seepage forces

The earthfill and foundation materials feature a wide range in elastic constants. In this study, the worse ground conditions were taken into account. Therefore, the minimum values of modulus of elasticity and Poisson's ratio were selected as 500×10^3 kN/m^2 and 0.2 for the foundation rock layer, 70×10^3 kN/m^2 and 0.3 for the clay core and 150×10^3 kN/m^2 and 0.3 for the sand gravel shell respectively. The shear strength parameters were considered as based on geomechanical classification and laboratory tests. The cohesion c and the angle of friction φ were taken as 24 kN/m^2 and 26 deg for the clay core and 1 kN/m^2 and 40 deg for the sand gravel shell. A complete list of the material properties used in the FE analyses are given in Gikas and Sakellariou (2008). Gravity load was considered in all models. In addition, water pressure and seepage forces were applied for the stages of first filling of the lake and the operation of the dam, as external loading conditions. Influence of minor geological features was eliminated to simulate a continuous media. In all models, the lower and side boundaries were restrained from moving vertically, whereas hydraulic conditions were applied on the fluid and seepage head of the dam (Figure 6).

5. DATA ANALYSIS AND DISCUSSION

In order to be able to compare the results of the FE modeling with those obtained from the surveying monitoring system, the geodetically derived displacement vectors were reduced to the specified cross-section locations adopted in the FE analysis. This was accomplished in two sequential steps. Firstly, the coordinates (x, y) of every station at the crest were transformed from the Old National grid coordinate system (based on the HATT azimuthal projection) to the local coordinate system (ξ, η), which is defined with respect to the cross-valley (parallel to the dam axis) direction as shown in Figure 7. Then, the transformed coordinates of the control points were interpolated to compute the horizontal movements at the eleven cross-section locations.

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} x_0 + x' \\ y_0 + y' \end{bmatrix}$$

$$\begin{bmatrix} \eta \\ \xi \end{bmatrix} = \begin{bmatrix} x_0 \\ y_0 \end{bmatrix} + \begin{bmatrix} \cos(\varphi) & -\sin(\varphi) \\ \sin(\varphi) & \cos(\varphi) \end{bmatrix} \begin{bmatrix} x' \\ y' \end{bmatrix}$$

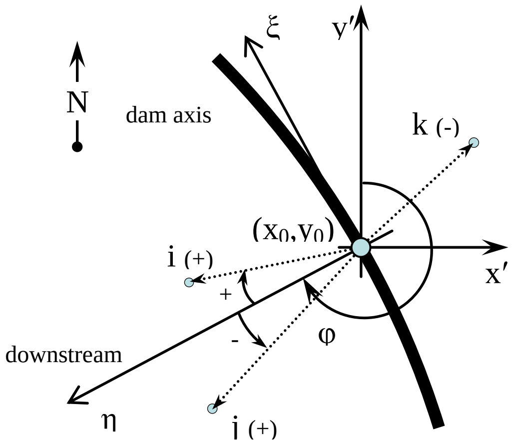

Figure 7: Coordinate transformations of computed displacements. Deflections pointing downstream are positive (upstream negative).

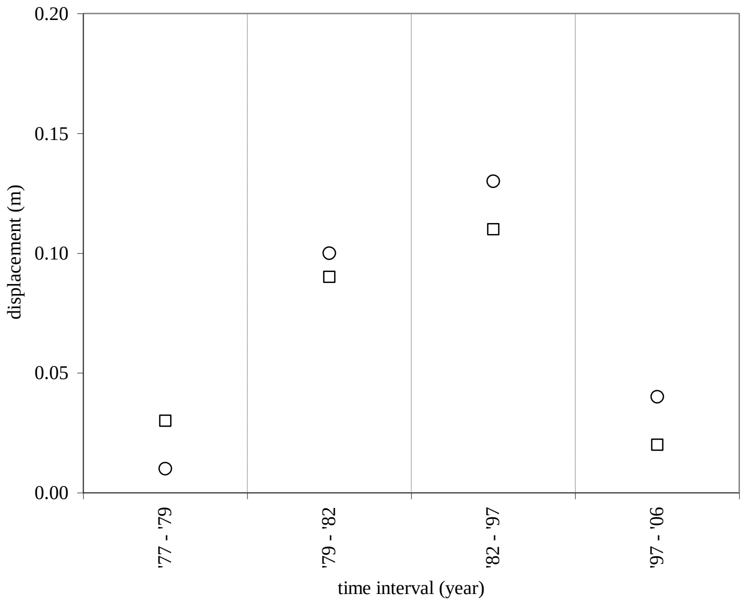

Figure 8: Horizontal displacements (η-component) at cross-section 6 (middle of the dam) estimated by geodetic observations and FE modeling. The periods 1979-1982 and 1982-2006 correspond to the stages of first filling of the reservoir and operation of the dam

Figure 8 shows the horizontal displacements (η-component) at cross-section 6 (located at the middle of the crest) obtained by FE modeling and geodetic monitoring. From this plot it is evident that the overall difference for a total period of 28 years is in the order of 2 cm. Furthermore, the symmetry of the deflection patterns observed between the various stages in the lifetime of the dam are similar, suggesting that, the assumptions made and the parameters (material type, boundary conditions, etc.) used in the FE modeling are correct.

Figure 9 depicts summary results derived by the FE analyses and the geodetic monitoring observations at the eleven cross-section locations. More specifically, it shows the differences between the two estimates in the accumulated horizontal movements (circles) in the time period 1979 - 2006, and the deviation in the orientation of the geodetically derived displacement vectors (rhombs) from the upstream-downstream direction for the same period of time. From this graph it is obvious that the differences in the magnitude of the displacements are small and vary from 1 cm - 3 cm. The relatively higher (6 cm) values observed towards the tail-ends of the crest are most likely to occur due to the assumptions pertaining to the two-dimensional plane-strain conditions used in the FE models. Also, as expected, the horizontal movements are pointing strongly downstream normal to the crest of the dam due to the loading by the reservoir. Overall, these results add further confirmation that the geodetic procedures followed and the implementation of the FE models are correct.

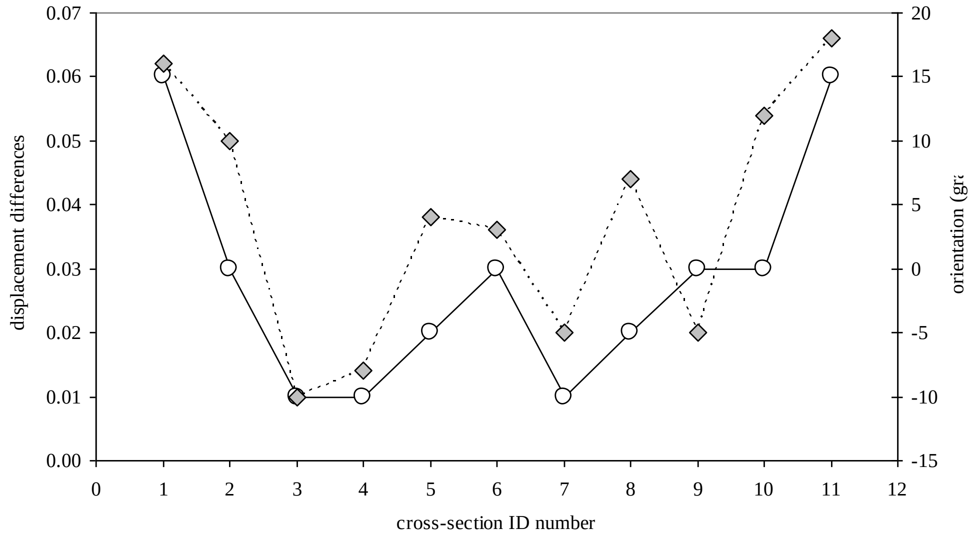

Figure 9: Differences in the horizontal displacements computed for the eleven cross-section locations at the crest of the dam between geodetic monitoring and FE modeling (circles), and deviation in the orientation of the geodetically derived displacement vectors from the upstream-downstream direction (rhombs) for the period 1979-2005

6. CONCLUSIONS

The analysis of the long-standing horizontal deflection monitoring record of the Mornos dam and its cross-examination with the results derived by the FE models indicates that the dam retains its structural integrity. Also, the results of independent settlement analysis studies of the same dam suggest similar conclusions. Such studies contribute to the understanding of the kinematics of dams and can prove useful for the design and structure of future constructions.

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