Deformation Studies of the Dam of Mornos Artificial Lake via Analysis of Geodetic Data

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Key words: GPS, Mornos dam, structural deformation, precise leveling

SUMMARY

Internal soil erosion, hydraulic gradients and stability problems resulting from high pore pressures are common causes of failure of embankment dams. However, the self-weight of a dam and variations in water pressure (resulting from the annual variation in water volume) may be a source of extensive deformation of its embankment and foundation that, potentially, may lead to a loss of stability of the structure. The Global Positioning System (GPS) provides a valuable tool for monitoring geospatial deformations, and thereby aids in understanding the complex structural and tectonic mechanisms related to the interaction of the water reservoir and the body of the dam.

The artificial lake of Mornos is located some 25 km north of the seismically active area of the Gulf of Corinth in central Greece. This lake serves as the main storage reservoir for the water supply of Athens. In the resent years, in order to study the structural deformation of Mornos dam four survey campaigns from 2002 – 2004 were carried out. This paper presents the results of the analysis of the GPS and precise leveling data collected spanning the entire period of observations.

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1. INTRODUCTION AND HISTORICAL OVERVIEW

In order to secure drinking water for the metropolis of Athens in Greece, an area where nearly 40% of the national population resides, construction began on Mornos dam in 1972 that led eight years later to the creation of the artificial lake of Mornos. The reservoir is situated in central Greece, just 7 km west of Lidoriki and approximately 220 km west-northwest of the city of Athens (Figure 1). The dam is one of the largest earthen gravity dams in Europe. It is 126 m high with a total crest length 825 m and crest width 10 m (Eydap 2004) – see Figure2. The area of the forming reservoir is 18,5 km^2 at a spillway level 435 m above sea level and maximum capacity 780 million m^3. The whole storage and the dam-site area are marked by a complicated tectonic structure. The reservoir is built of typical flysch rocks and fine to medium grained sandstone. At the dam site, the left abutment consists mainly of solid massive sandstone. In contrast, the right abutment in the part below the valley floor level consists of weak tectonite, whereas in the upper part of the slope predominate flysch structures (Lahmeyer International 1976).

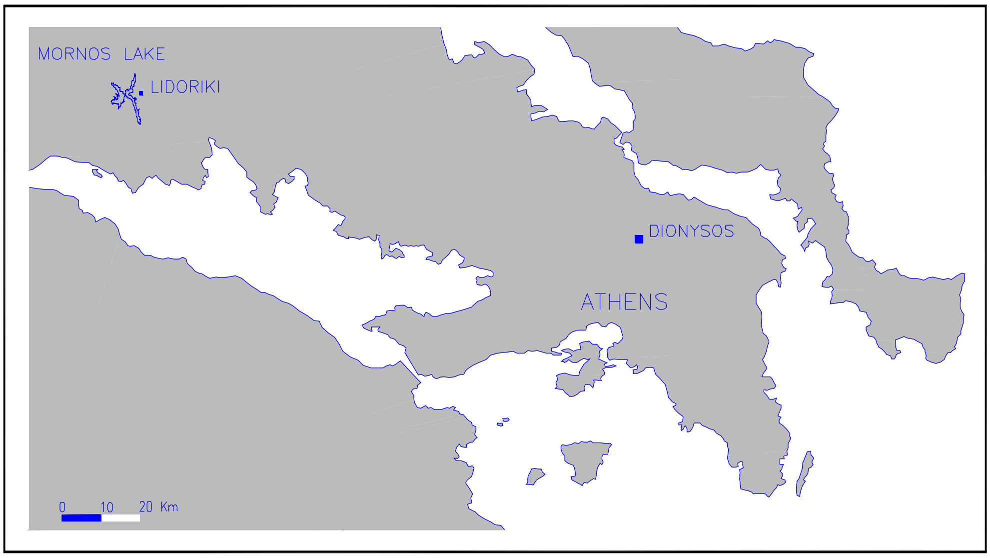

Figure 1: Location map of the Mornos Artificial lake.

The technical characteristics of the dam in combination with the intensively disordered geological formations of the wider area has led to the adoption of a detailed monitoring program to include among other forms of measurements extensive geodetic deformation surveys. Depending on the goals of observation, two types of structural deformation surveys have been undertaken. First, in order to study the crustal behavior of the greater area of the Mornos reservoir, five GPS campaigns were carried out from 1993 to 2003. From these studies, it can be concluded that the area surrounding the reservoir exhibits similar tectonic behavior and follows the general trends observed in central Greece from independent research work (Avallone et al. 2004, Billiris et al. 1991, Briole et al. 2000). However, these results will not be elaborated any longer in this study. In addition to crystal mobility studies, periodic monitoring surveys have been undertaken since the completion of the dam to determine horizontal and vertical displacements at selected points along the crest and the inspection galleries of the dam. Up to 1998, these surveys employed conventional geodetic instruments and techniques whereas in the most recent years (2002-2004) satellite (GPS) deformation survey methods were implemented. However, due to the intrinsic limiting factors of the GPS system as to height determination, monitoring of the vertical displacements has been accomplished solely by means of geometric leveling techniques.

This paper is confined in the survey campaigns undertaken in the time interval 2002-2004. It describes the design of the monitoring network and presents the analysis and the results obtained with GPS and precise leveling measurements during the four consecutive survey campaigns.

Figure 2: Upstream view of the Mornos dam and its surroundings.

2. NETWORK DESIGN AND FIELD DATA COLLECTION

Four independent surveys were conducted between 2002 and 2004. The first and second surveys were undertaken during the rainy and dry seasons in mid November 2002 and in mid April 2003 respectively. To ensure that deformation data will be available at regular time intervals, the third and fourth surveys were conducted in mid October 2003 and in mid April 2004. The configuration of the observed GPS network is shown in Figure 3. This network comprises 17 stations established on the dam body every 50 m and 4 stations established at selected points on the ground surrounding the dam. A base station (HYDR) was set up on stable ground 6 km east-northeast of the dam area and was run continuously throughout the period of observations. Considering its very good sky view, this base station was used as a reference station for relative positioning in the post-processing mode. In this project five dual frequency GPS receivers were used. In order to facilitate field procedures and save observation time one receiver was set up on station F017 (located in the middle of the crest) and recorded continuously. This receiver was acted as an "intermediary" for computing the coordinates from HYDR station to all other points. Under this observation scheme any baseline from station F017 to any node in the network was less than 400 m long resulting in session lengths of the order of one hour. Data was collected with 15 sec interval and 15 degrees cut-off angle.

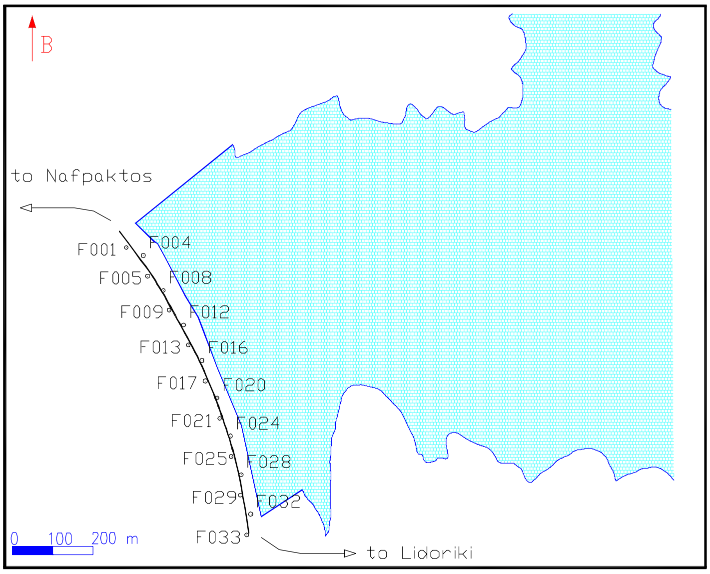

Figure 3: The GPS stations used along the crest of the Mornos dam.

Precise leveling is a more accurate method for evaluating vertical deformations compared to GPS derived measurements (Kasser and Becker 1999). Hence, in a similar manner followed in the past years, a leveling line that included the same network stations used for GPS monitoring was measured to determine vertical displacements along the crest of the dam. In order to control errors pertaining to the measurement process observations began and ended at the same reference point to perform, thus, a double run leveling. The leveling line was well over 1 km long and the misclosure tolerance for accepting a line was 1 mm. Geometric leveling measurements were scheduled to fall before or after the GPS sessions and were carried out by using a Leica NA2 level carrying an optical micrometer.

3. GPS DATA PROCESSING

The coordinates of HYDR station (and consequently of all other points in the network) were computed in the International Terrestrial Frame 1996 (ITRF '96). At first, GPS data were collected for a relatively short period of time (four days plus) from both permanent International GPS Service (IGS) sites and the continuously recording station of DIONYSOS – a monitoring station that is situated nearby Athens and it is operated by the Satellite Geodetic

Observatory of Dionysos of NTUA. These data sets were processed using precise orbits and they allowed DIONYSOS station to be linked to the ITRF ’96. Finally, simultaneous observations from both DIONYSOS and HYDR stations were processed to produce absolute positioning of HYDR station in the ITRF ’96.

The GPS data was processed with Bernise 4.2 scientific software developed by the University of Bern (Hugentobler et al. 2001). The unknown ambiguity numbers were fixed correctly to their integer values using the Quasi Ionosphere Free (QIF) method – see Figure 4. In contrast, the final solution for small baselines (< 10 km) was derived directly from the L1 ambiguity resolution in order to avoid the noise amplification introduced by using the L3 linear combination (Hugentobler et al. 2001, Leick 2003).

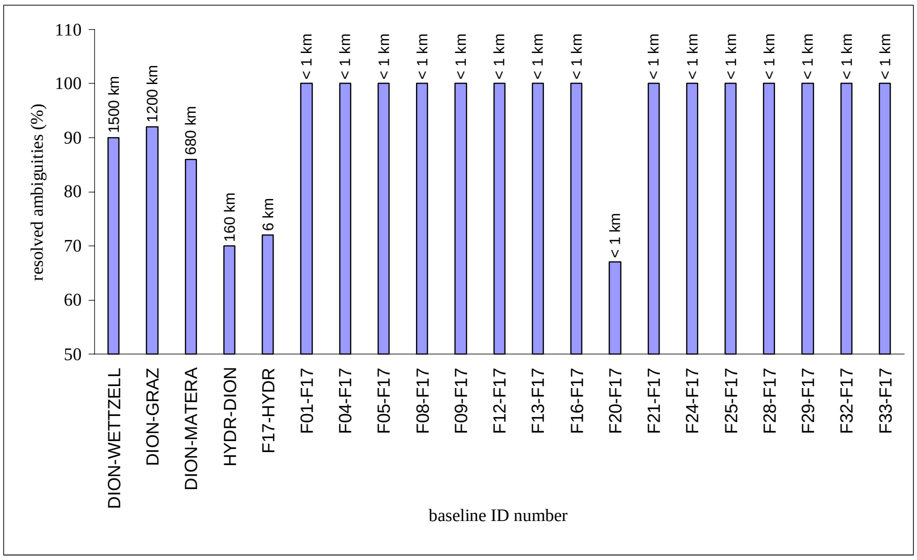

Figure 4: Percentages of successfully resolved ambiguities.

4. DATA ANALYSIS AND COMPARISONS

In this study, geospatial displacements were obtained by differentiating the coordinates of GPS stations and their corresponding orthometric heights computed from consecutive surveys. In fact, three deformation phases are considered. Phases A, B and C correspond to the time intervals between the observation periods from Nov. ‘02 to April ‘03, from April ’03 to Oct. ’03 and from Oct ’03 to April ’04 respectively.

4.1 GPS Data Evaluation

From the baseline solution obtained for each survey, point coordinates of all stations in the network were computed. As detailed in Section 3.0, in order to facilitate coordinate comparisons between observation periods these coordinates were reduced to a common datum (ITRF ’96). Based on these values, coordinate differences were then computed for every station occupied on the crest for phases A, B and C. Finally, in order to aid interpretation, the coordinate differences were rotated to their corresponding North and East components.

Figures 5, 6 and 7 map the vectors of coordinate differences for all stations occupied on the crest and around the dam area for phases A, B and C respectively. Table 1 depicts the same information in a more concise form and in relation to changes in the water volume in the reservoir for the time intervals in question. A close examination of these plots would lead up to a number of observations. At first, if phases A and B are considered, most stations experience horizontal displacements of the order of 10-15 mm. However, it is of great importance to note the directional distribution of the displacement vectors. From Figure 5 it is immediately evident that most stations exhibit displacement vectors in a direction almost perpendicular to the embankment centerline pointing downstream. This is to be expected given that the water volume in the reservoir was over-doubled during phase A. The opposite phenomenon is observed during phase B. At the beginning and towards the end of phase B, the reservoir contains almost the same water volume. However, during the dry season the water reserves were significantly reduced. Probably this could partly explain the overall trend of the displacements shown in Figure 6. During phase C, the dam axis does not exhibit any obvious reaction in response to the water volume variations.

In the past, previous studies based on conventional geodetic methods have shown much bigger displacement values. Nevertheless, in the most recent years (1997-2004), it appears that horizontal displacements have been decreased and stabilized suggesting that the dam body itself has settled.

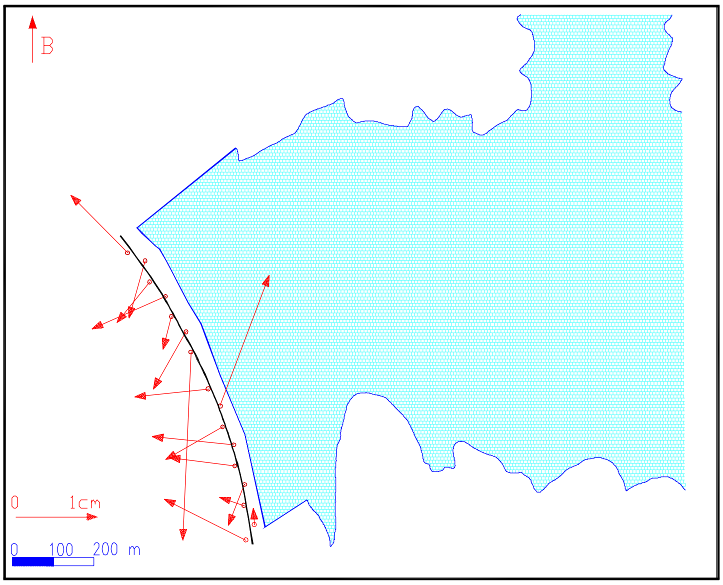

Figure 5: Horizontal displacement vectors computed for the stations located on the crest of the dam for phase A (Nov. ’02 - Apr. ’03).

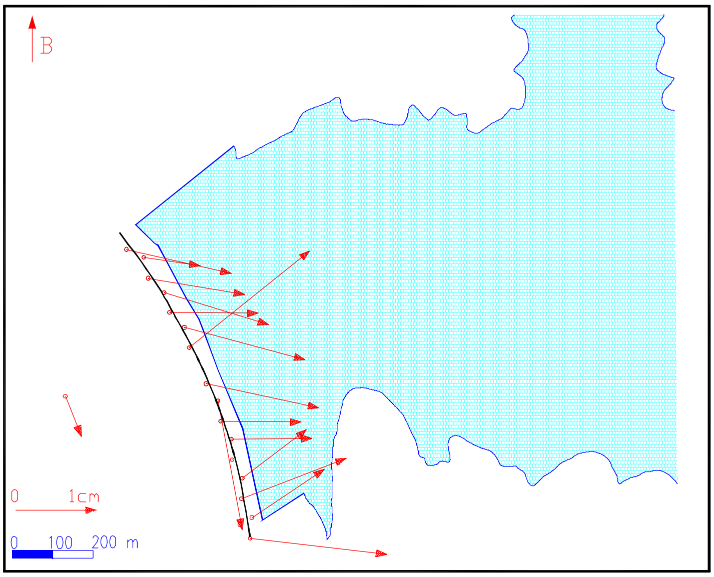

Figure 6: Horizontal displacement vectors computed for the stations located on the crest of the dam for phase B (Apr. ’03 - Oct. ’03).

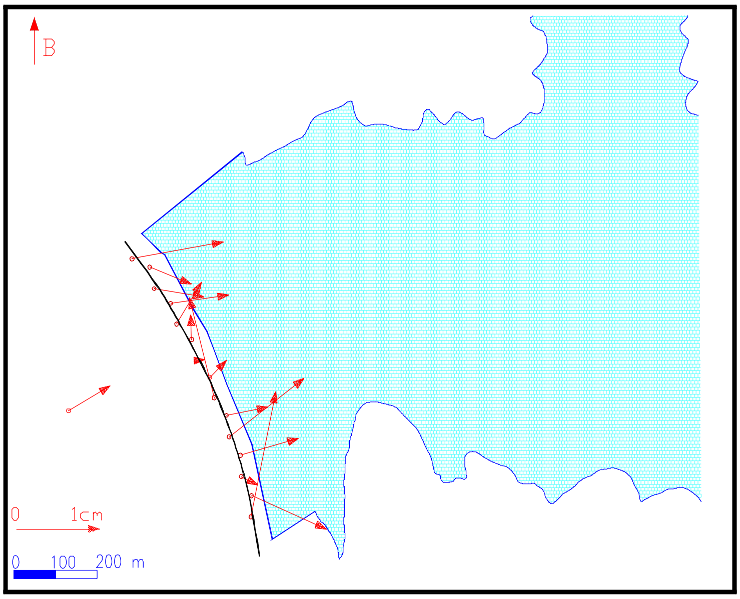

Figure 7: Horizontal displacement vectors computed for the stations located on the crest of the dam for phase C (Oct. ’03 - Apr. ’04).

time period		PHASE A Nov 02 – Apr 03	PHASE B Apr 03 – Oct 03	PHASE C Oct 03 – Apr 04
variation in water volume (m^3 x 10^6)		240 → 540	540 → 512	512 → 680
horizontal displacement (mm)	mean	9	13	8
	max	23	19	17

Table 1: Indicative values of the horizontal displacements computed for the stations located along the crest of the dam versus water volume variation in the reservoir during phases A, B and C.

4.2 Precise Leveling Data Evaluation

As discussed in Section 2.0 double run leveling was performed to provide elevation determination for the 17 pillars occupied along the crest of the dam. Figure 8 shows the height differences computed between successive epochs, namely for phases A, B and C. During phase A the dam axis, surprisingly, seems to be slightly risen in the middle and settled in the tail ends. However, these changes are just over the estimated displacement uncertainty; and hence, a clear statement cannot be drawn. In the time interval between the second and third surveys (phase B), the dam exhibits a clear settlement at all 17 stations with a maximum value of 17 mm. Minimum values are observed at both ends of the dam's crest. Values of significant displacement are also observed in phase C; however, their pattern is more complicated. In certain cases the observed differences between successive stations are of the order of 9 mm. This could be partly be explained by the fact that neighboring pillars are established at opposite locations on the dam crest (i.e. facing upstream and downstream respectively – see Figure 3).

As a whole, these results are in consistency with those obtained in the past. Figure 9 depicts a synopsis of the vertical displacements observed on the monuments established in the middle and the tail ends of the crest for the entire lifetime of the dam. From this plot it is immediately evident that vertical displacements between observation periods are permanent. As expected, maximum values are observed at the stage of filling the reservoir and during the first years of operation. For certain observation periods the vertical deflection can reach in the middle of the dam as much as 80 mm.

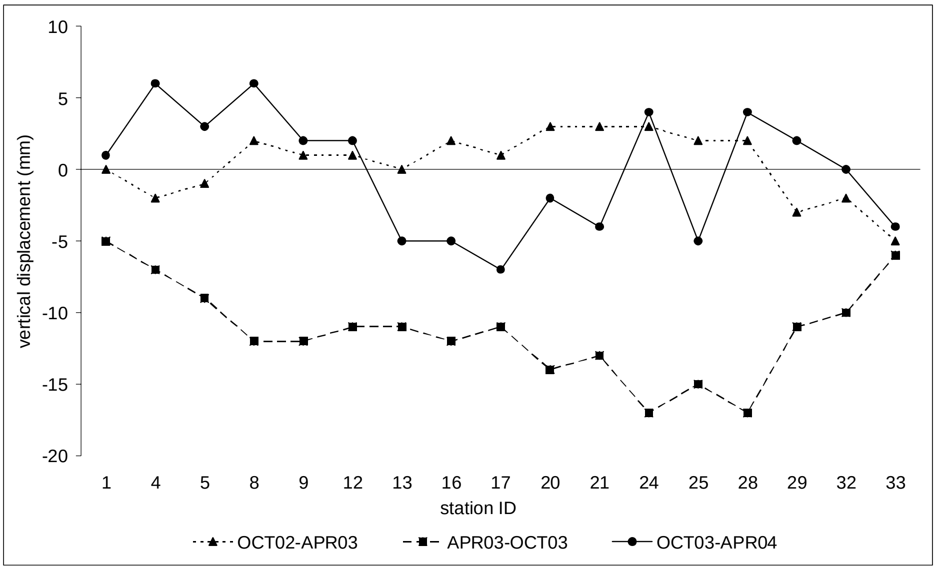

Figure 8: Vertical displacement values computed for the stations located on the crest of the dam during phases A, B and C.

5. CONCLUSIONS

Geodetic monitoring of Mornos dam since 1977 confirms that changes in its appearance have been gradual. Recent crest surveys based on GPS and precise leveling data have consistently provided evidence that the deformation pattern established years ago has developed or matured only slightly. This observation is verified from the analysis of geometric leveling data collected in the past years along the inspection galleries and the shafts of the dam. However, variations in the static loading conditions, attributed to periodic variations in the water volume in the reservoir, have resulted in detectable deviations from the prevalent settlement pattern in the short to medium term.

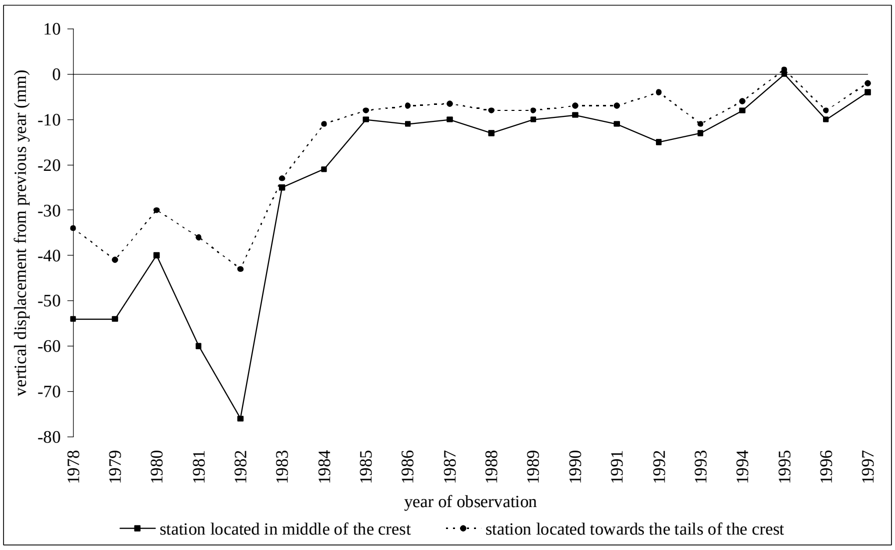

Figure 9: Vertical displacement values computed at selected points on the crest of the dam during 1978 – 1997.

The artificial lake of Mornos is probably the most considerable in a sequence of a large-scale water works that were constructed in order to secure drinking water for the city of Athens. As such, its significance for the city of Athens and its value to the owner are beyond price. Hence, it is imperative that, regardless of the age of the dam, periodic monitoring should continue on. Finally, it is emphasized that the dam lies within the seismically active area of central Greece. This further implies the need of precise correlation of obligatory dam deformation measurements and recent movements of the earth crust in the greater area.

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BIOGRAPHICAL NOTES

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Vassilis Gikas joined as a lecturer the National Technical University of Athens in 2004. His previous appointments include a research position in the Department of Geomatics, University of Newcastle upon Tyne, UK. In the past he served the offshore industry in the UK and the USA as a navigation and positioning specialist and more recently, he served the private sector in a series of surveying and transportation engineering projects under the same capacity. His principal areas or research include navigation, high precise GPS and surveying engineering applications.

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