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Finite element analysis of earth dam settlements due to seasonal reservoir level changes

Analyse par éléments finis des tassements en terre en raison des changements saisonniers du niveau du réservoir

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ABSTRACT: This paper presents a nonlinear finite-element analysis of the long-term (>25 years) deformations of an earth dam. The Kouris earth dam, which is largest dam in Cyprus and for which comprehensive monitoring data is available, is taken as the case study. The study attempts to examine the effects of reservoir level variation and transient soil consolidation on the long-term settlements of earth dams.
Two-dimensional plane-strain coupled transient hydro-mechanical nonlinear finite-element analyses of the dam are conducted. The numerical model considers soil plasticity, nonlinear stiffness and permeability of the different earth and dam materials. The entire stress history of the dam is modelled, which includes staged construction, reservoir impounding, consolidation and seasonal reservoir level changes.
This study shows that seasonal reservoir level changes induce small fluctuations of crest settlements and that the majority of the total settlements is due to soil consolidation. The effect of different material properties (e.g. stiffness and permeability) on the dam deformations are examined along with the applicability of different constitutive models. The results are useful in understanding the mechanisms governing the long-term settlements of earth dams.

RÉSUMÉ: L'analyse par éléments finis du barrage de terre est effectuée. Les règlements à long terme sont prévus. Une bonne comparaison entre les calculs et les mesures est obtenue.

Keywords: earth dams, embankments, reservoir, finite element analysis, seepage, consolidation

1 INTRODUCTION

Long-term maintenance of earth dams is important as this is crucial for their resilience and safety. The International Committee on Large Dams – ICOLD has identified some major threats for dam safety which include seismic activity (Elgamal et al., 1990; Kontoe et al., 2013; 2019; Pelecanos et al., 2013; 2015; 2016; 2018a; 2019a; 2019b; Shire et al., 2013), internal erosion (Bridle & Fell, 2013; Shire & O'Sullivan, 2013, 2016), faulting, climate variation and change (Pytharouli & Stiros, 2005; Gikas & Sakellariou, 2008), hydraulic fracture etc. Climate changes may influence significantly dam performance as large seasonal variations (e.g. hot summers and cold winters) result in significant reservoir level changes which further affect the water pressures within the dam and the entire stress regime. It is therefore important to understand the impact of climate changes on the behaviour of earth dams and be able to predict and quantify its effects, especially if they become a threat for the dam's safety.

Many investigations have been carried out over the years which considered field monitoring (Kyrou et al., 2005; Dounias et al., 2012; Ventrella et al., 2019), laboratory experiments and computational simulations (Tedd et al., 1997; Alonso, 2005; Charles et al., 2008; Pelecanos et al., 2017; 2018b) for understanding dam performance and safety under various climate conditions. Many of these studies have raised the issue of reservoir-induced dam deformations and attempted to quantify this interaction. However, this is not an easy task and therefore more studies are needed in order to fully understand the effects of reservoir level changes on dam deformations and safety.

This study presents a computational analysis of field monitored behavior of an instrumented earth dam, the Kouris dam, which is the largest dam in Cyprus. It aims to understand the effects of long-term environmental actions, such as reservoir level changes, on the behaviour of earth dams. The displacement data from over 25 years are available and nonlinear finite element analyses are performed to model the entire stress history of the dam, including construction, reservoir impoundment and reservoir level changes. The numerical analyses confirm the observed hypothesis that reservoir level changes affect the deformations of the dam crest.

2 KOURIS DAM

Kouris dam is the largest and tallest dam in Cyprus. It is a zoned earth-rockfill operated by the Cyprus Water Development Department (WDD) and serves as the main water storage facility in the country. It was built during 1984-1988 and its embankment consists of a central clay core of low permeability, followed by thin layers of fine and coarse filters. The upstream shell consists of terrace gravels, which are adjacent to the upstream filters and then river gravels covered by rip rap on the upstream dam slope with a small cofferdam at the upstream dam toe. The downstream shell consists in its entirety by terrace gravels with talus deposits, which rest on a thin drainage gallery. Its crest is 570m long and the embankment is 112m high with the highest level of its reservoir at 102m, and its total reservoir capacity is 115 million m^3. Figure 1 shows a cross-sectional view with the various soil layers.

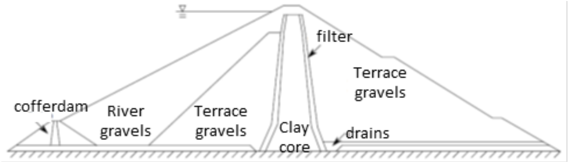


Figure 1. Geometry of the dam

Three independent instrumentation sets are installed on the dam providing monitoring data about the deformations of the dam: (a) Embankment Crest Movement Indicators (ECMI), (b) a vertical geodetic network and (c) a three-dimensional (3D) geodetic network.

The first instrumentation network, installed in 1991, consists of an observation pillar, (fixed point) and six embankment crest movement indicators (ECMI) installed at the time of construction. The measurements of these points are being carried out (irregularly, monthly or bi-monthly) since 1990 by the Cyprus WDD. The horizontal distance and the height difference of each ECMI from the pillar was determined using a Leica TC1101 total station, which provides accuracy of ±2mm ±2ppm for the distance measurements and ±1" for the angle measurements.

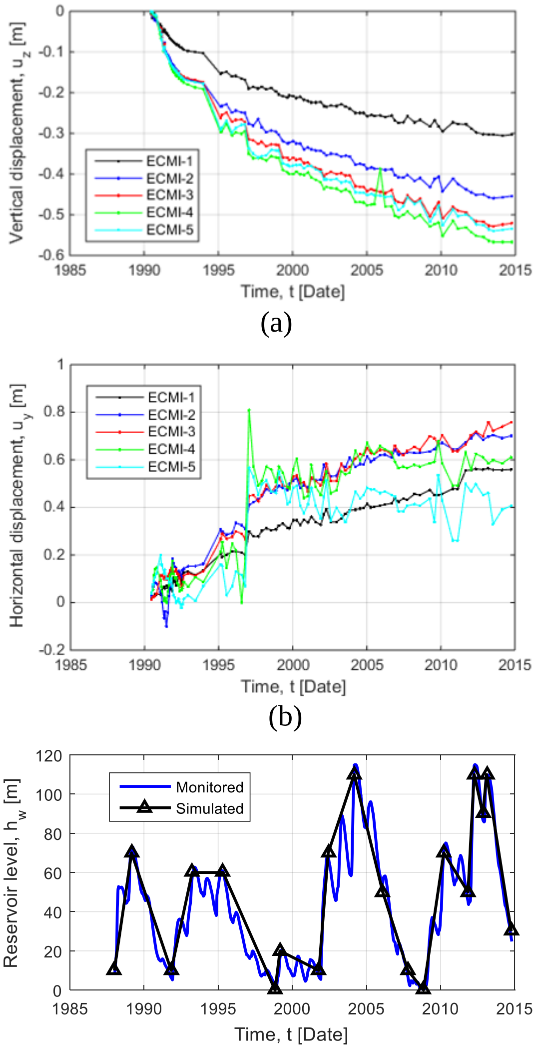
Additionally, two modern geodetic networks were installed in 2006. A vertical (1D) and a three-dimensional (3D) control network. Generally, deformation monitoring is applied by the establishment, the measurement and the adjustment of such network. The vertical control network was established in 2006 (Constantinou, 2013). It consists of 7 control points. Six of them (R1-R6) are bronze benchmarks, located along both sides of the wall on the road at the crest of the dam and in a distance of about 100m between each other. The seventh point is the pillar T2 about 1 km far away, which serves as the fixed reference point of the network.

Three periods of measurements (July and December 2006 (Temenos, 2007) and June 2012 (Pantelidou, 2013)) were carried out for the determination of the height differences between the points by using either (a) the spirit leveling method, or (b) the accurate trigonometric heighting method (Lambrou, 2007; Lambrou & Pantazis, 2007, 2010). The latter two modern systems are extremely robust and much more accurate than the old initial system. Figure 2 shows the position of the instruments on the dam.

Figure 2. Instrumentation on the dam crest

3 MONITORING DATA

Figure 3 (a) shows the time-histories of dam crest settlements for the entire monitoring period. It is shown that there is a trend for downward movements which concentrate more at the midcrest of the dam. Also, Figure 3 (b) shows the time-histories of the horizontal crest movements. The latter figure suggests that there are downstream crest movements that develop with the time. Finally, Figure 3 (c) shows the fluctuations of the reservoir level which seem to follow a seasonal variation, i.e. to follow the winter-summer cycles. On the same plot, the monitored steps of the Finite Element analysis (see later sections) are also plotted for comparison. More details about the monitoring data may be found from Ventrella et al., (2019).



(a)

(b)

(c)

Figure 3. Dam deformations: profiles of (a) vertical and (b) horizontal dam crest displacements.

4 FINITE ELEMENT MODEL

To better understand the response of the dam to environmental changes, relevant finite element analysis was conducted. This was to explore the long-term dam behaviour and shed some light on the physical processes involved which governed the observed long-term settlements of the dam crest. More specifically, such an analysis would allow a comparison between the relative effects of soil consolidation and reservoir level fluctuations.

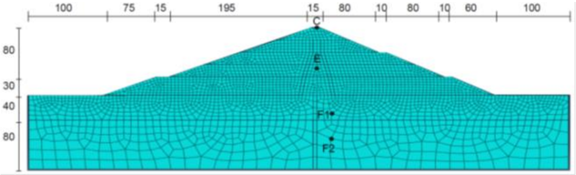


Figure 4. The FE mesh employed.

Two-dimensional (2D) plane-strain non-linear elasto-plastic transient coupled-consolidation finite element (FE) analyses were performed with the FE software ABAQUS/Implicit. The dam and the foundation underneath were discretized with 2540 finite 8-noded quadratic iso-parametric elements with 16 displacement and 4 pore water pressure degrees-of-freedom (CPE8RP). The FE mesh (Figure 4) includes the clay core, the core filters, the rockfill shells, the grout curtain and two layers of foundation material. The materials are modeled as elasto-plastic consolidating. The elasto-plastic constitutive model adopted is the Mohr-Coulomb (MC) coupled with a hyperbolic small-strain stiffness that dictates the non-linear stiffness degradation of shear modulus, G, with the shear strain, γ, (similar to Pelecanos et al. (2015)) given by Equation 1 and combined with a constant Poisson's ratio, ν.

$$\tau = \frac{G_{max} \cdot \gamma}{1 + \lambda \cdot \gamma} \tag{1}$$

Where, G is the soil shear modulus (=E/2(1+ν)), E is the soil Young's modulus, Gmax is the maximum value of G for zero shear strain, γ is the shear strain and λ is a model calibration parameter. The latter parameter dictates shear stiffness degradation with strain. However, due to lack of relevant experimental data (the design of the dam was performed in the 1970-80s), the hyperbolic model was calibrated against appropriate empirical curves from the literature, using Vucetic & Dobry (1991) were used for the cohesive clay core and the foundation materials (including the grout curtain) and the Rollins et al. (1998) curves for the granular filters and the rockfill shells.

Table 1. Summary of known material properties.

Material	E [MPa]	φ [deg]	c [kPa]	k [m/s]	λ []
Filter	300	45	37	10^{-3}	2500
Rockfill	400	45	37	10^{-3}	2500
Foundation	700	45	35	10^{-8}	900
Clay core	300	45	40	10^{-9}	900

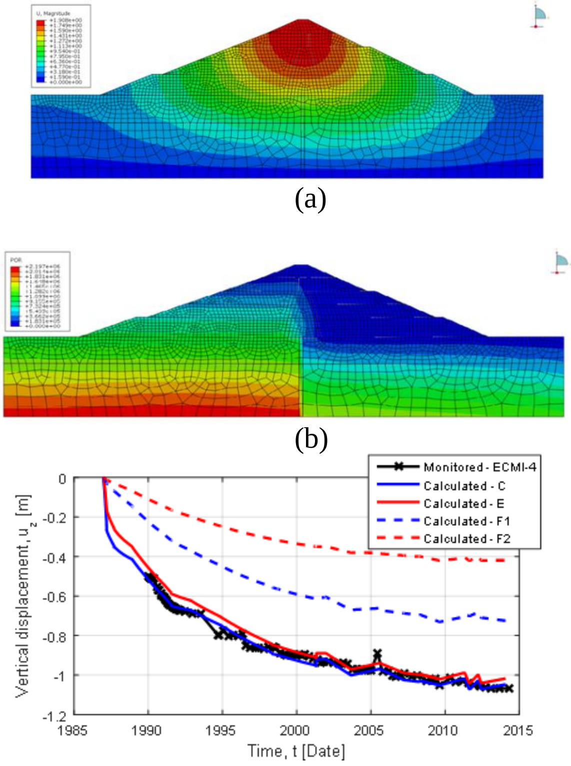
The analysis was performed over a number of steps in order to simulate the appropriate stress history of the dam. Firstly, initial stresses were generated with level ground (i.e. riverbed) and subsequently the embankment was constructed in successive layers within 12 months and finally the reservoir impoundment took place. Then, the operation of the dam was simulated including consolidation and the associated fluctuations of the reservoir which followed the monitored time-history of the level of the reservoir, as shown in Figure 3(c).

5 COMPUTATIONAL ANALYSIS RESULTS

The results of the FE analysis are shown in Figure 5. Figure 5 (a) shows the resultant displacements of the nodes at the case of full reservoir, and it can clearly be observed that most of the deformations are located close to the dam crest. Moreover, Figure 5 (b) shows the pore water pressure distribution within the dam at the time of full reservoir. This reveals the saturation of the upstream rockfill and the reduction of the hydraulic head within the centre due to the seepage through the low-permeability clay core and grout curtain. Figure 5 (c) presents the time-hisotry of vertical displacements at selected points in the dam (C: crest, E: mid-height of Embankment height, F1: shallow point in the foundation, F2: deep point in the foundation).

It is observed that there is generally a good match between the field-monitored (from ECMI-4) and numerically-predicted displacement time-histories. A general trend of downward movements can be observed which is attributed to the consolidation of the dam materials. This means that the reservoir fluctuations do not appear to have significant effect on the settlements. The vertical displacements within the embankment and the two foundation layers (Points E, F1 and F2) are presented as well. It may be observed that the consolidation settlement values of the foundation layers are significantly large and comparable to those of the dam crest, which may suggest that the consolidation settlements within both the dam embankment and the foundation dominate the total crest settlements. This is believed to be due to the dissipation of the excess pore water pressure built-up in the embankment and the low-permeability foundation because of the construction of the large dam.

It is also postulated that reservoir level fluctuations do not contribute very substantially and instead the dominant mechanism inducing long-term vertical crest displacements is consolidation of the soil. It is therefore concluded that there is no major influence from the reservoir fluctuations implying that the majority of displacements is due to long-term soil consolidation.



(a)

(b)

(c)

Figure 5. Analysis results: (a) resultant deformations, (b) pore water pressures and (c) time-histories of vertical crest displacements.

6 CONCLUSIONS

This work investigates numerically the long-term settlement response of earth dams due to climate changes leading to variations of the reservoir level. The investigation adopts nonlinear finite element modelling to analyse the long-term deformation behaviour of a well-instrumented dam and compare the numerical predictions with recorded data.

The numerical model was analysed using the nonlinear finite element method, considering hydro-mechanical coupling and elasto-plastic soil behaviour with nonlinear elasticity prior to material yield.

The findings of this study may be summarised as follows:

(a) Consolidation of the dam embankment and foundation materials following the construction of the dam appears to be the main reason for the long-term dam settlements.

(b) The contribution of reservoir level fluctuations on the displacements of the dam was found to be small compared to that of long-term consolidation.

Further analysis of the monitored response of Kouris dam, including processing in the frequency domain and mathematical correlations between dam crest settlements and reservoir fluctuations may be found from Ventrella et al. (2019).

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8 REFERENCES

Alonso, E.E., Olivella, S. and Pinyol, N.M., 2005. A review of Beliche Dam. *Géotechnique*, **55**, 267-285.

Bridle, R. and Fell, R. eds., 2013. Internal erosion of existing dams, levees and dykes, and their foundations. Bulletin **164**, *Volume 1: Internal Erosion Processes and Engineering Assessment*.

Charles, J.A., 2008. The engineering behaviour of fill materials: the use, misuse and disuse of case histories. *Géotechnique*, **58**, 541-570.

Constantinou, C., 2013, Monitoring the defromation of Kouris dam in Cyprus by using GNSS measurements. *Diploma thesis* (in Greek), Cyprus University of Technology, Cyprus.

Dounias, G.T., Anastasopoulos, K. and Kountouris, A., 2012. Long-term behaviour of embankment dams: seven Greek dams. *Proceedings of the Institution of Civil Engineers-Geotechnical Engineering*, **165**, 157-177.

Elgamal, A.W.M., Scott, R.F., Succarieh, M.F. and Yan, L., 1990. La Villita dam response during five earthquakes including permanent deformation. *Journal of Geotechnical Engineering*, **116**, 1443-1462.

Gikas, V. and Sakellariou, M., 2008. Settlement analysis of the Mornos earth dam (Greece): Evidence from numerical modeling and geodetic monitoring. *Engineering Structures*, 30, 3074-3081.

Kontoe, S., Pelecanos, L. & Potts, D., 2013. An important pitfall of pseudo-static finite element analysis. *Computers and Geotechnics*, **48**, 41-50.

Kontoe, S., Zdravkovic, L., Han, B. & Pelecanos, L., 2019. *Hydrodynamic effects and hydromechanical coupling in the seismic response of dams*. 7th International Conference on Earthquake Geotechnical Engineering. Rome, Italy

Kyrou, K., Penman, A. and Artemis, C., 2005. The first 30 years of Lefkara Dam. *Proceedings of the Institution of Civil Engineers-Geotechnical Engineering*, **158**, 113-122.

Lambrou, E., 2007, Accurate definition of altitude difference with geodetic total stations (in Greek), *Technika Chronika*, vol. **10**, 37-46.

Lambrou, E. and Pantazis, G., 2007, A convenient method for accurate height differences determination, Sofia.

Lambrou, E. and Pantazis, G., 2010, *Applied Geodesy*, Athens: Ziti.

Lomb, N.R., 1976. Least-squares frequency analysis of unequally spaced data. *Astrophysics and space science*, **39**, 447-462.

Pantelidou, A., 2013, Monitoring the vertical displacements of Kouris dam in Cyprus by usng modern accurate methods. *Diploma thesis* (in Greek), Cyprus University of Technology, Cyprus.

Pelecanos, L., 2013. Seismic response and analysis of earth dams. London, United Kingdom: *PhD thesis*, Imperial College London.

Pelecanos, L., Kontoe, S. & Zdravkovic, L., 2013. Numerical modelling of hydrodynamic pressures on dams. *Computers and Geotechnics*, **53**, 68-82.

Pelecanos, L., Kontoe, S. & Zdravkovic, L., 2015. A case study on the seismic performance of earth dams. *Geotechnique*, **65**, 923-35.

Pelecanos, L., Kontoe, S. & Zdravkovic, L., 2016. Dam-reservoir interaction effects in the elastic dynamic response ofconcrete and earth dams. *Soil Dynamics and Earthquake Engineering*., **82**, 138-41.

Pelecanos, L, Skarlatos, D & Pantazis, G., 2017, *Dam Performance And Safety In Tropical Climates – Recent Developments On Field Monitoring And Computational Analysis*. 8th International Conference on Structural Engineering and Construction Management, Kandy, Sri Lanka.

Pelecanos, L., Kontoe, S. & Zdravkovic, L., 2018a. The Effects of Dam–Reservoir Interaction on the Nonlinear Seismic Response of Earth Dams. *Journal of Earthquake Engineering*., 1453409.

Pelecanos, L, Skarlatos, D and Pantazis, G., 2018b, *Finite element analysis of the monitored long-term settlement behaviour of Kouris earth dam in Cyprus*. 9th European Conference on Numerical Methods in Geotechnical Engineering, Porto, Portugal

Pelecanos, L., Kontoe, S. & Zdravkovic, L., 2019a. *Seismic response of earth dams in narrow canyons*. 7th International Conference on Earthquake Geotechnical Engineering. Rome, Italy.

Pelecanos, L., Kontoe, S. & Zdravkovic, L., 2019b. *Nonlinear seismic response of earth dams due to dam-reservoir interaction*. The XVII European Conference on Soil Mechanics and Geotechnical Engineering, Reykjavik, Iceland.

Pytharouli, S.I. and Stiros, S.C., 2005. Ladon dam (Greece) deformation and reservoir level fluctuations: evidence for a causative relationship from the spectral analysis of a geodetic monitoring record. *Engineering Structures*, **27**, 361-370.

Rollins, K., Evans, M., Diehl, N. & Daily, W., 1998. Shear modulus and damping relations for gravel. *J. Geotechnical and Geoenvironmental Engineering, ASCE*, **124**, 396-405.

Scargle, J.D., 1982. Studies in astronomical time series analysis. II-Statistical aspects of spectral analysis of unevenly spaced data. *The Astrophysical Journal*, **263**, 835-853.

Shire, T. and O’Sullivan, C., 2013. Micromechanical assessment of an internal stability criterion. *Acta Geotechnica*, **8**, 81-90.

Shire, T. and O'Sullivan, C., 2016. Constriction size distributions of granular filters: a numerical study. *Géotechnique*, **66**, 826-839.

Shire, T., Pelecanos, L., Han, B. and Taylor, H., 2013. Current research in embankment dam engineering at Imperial College London. *Dams and Reservoirs*, **23**, 25-28.

Tedd, P., Charles, C.J.A., Holton, I.R. and Robertshaw, A.C., 1997. The effect of reservoir drawdown and long-term consolidation on the deformation of old embankment dams. *Géotechnique*, **47**, pp.33-48.

Temenos, C., 2007, Monitoring the deformations of Kouris dams in Cyprus. Diploma thesis (in Greek). *Diploma Thesis*, National Technical University of Athens, Greece.

Vucetic, M. & Dobry, R., 1991. Effect of soil plasticity on cyclic soil response. *J. Geotechnical Engineering, ASCE*, **117**, 87-107.

Ventrella, C., Pelecanos, L, Skarlatos, D and Pantazis, G., 2019, *Statistical analysis of long-term earth dam settlements*. The XVII European Conference on Soil Mechanics and Geotechnical Engineering, Reykjavik, Iceland