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Hygrothermal Performance in Underground Heritage Structures and Issues Related to their Conservation

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Abstract : *This paper presents the monitoring of the hygrothermal conditions in underground tombs named Macedonian tombs, in the district of Pella in north Greece and discusses the issues arising for their conservation. Systematic monitoring was conducted in the Doric tomb D and data as the material properties, the climate of Pella, the relative humidity and air temperature values in the burial chambers were analysed and discussed. The scope was to evaluate the changes of the temperature and relative humidity inside the tomb's chambers, depending on the external climatic conditions. Numerical simulation shows that complex processes take place on annual and daily basis into the mass of the building components of the tomb. These deterioration processes depend mostly on the changes of the boundary climatic conditions. The structural component of the tomb's façade is mostly vulnerable to periodical changes of the outdoor climate conditions. This is very important, if we consider the fact that the plaster covering the façade is often the supportive layer for historically valuable wall decorations Detailed interpretation and concluding results of the numerical simulation are presented in this paper.*

Keywords - *Heritage structures, Macedonian tombs, Monitoring, Numerical simulation*

I. INTRODUCTION

Interventions in underground heritage structures require extensive and objective knowledge of what one will be working with. "The multifaceted aspect of this work tends to encompass a growing number of specialities, with special emphasis on learning the causes of the factors that affect these buildings and the possible treatments that can solve them". [1] Moisture transfer in walls is responsible for many building pathologies. Water can act as an indirect aggressive agent accelerating or facilitating the progress of various destructive procedures.

Subterranean monuments, as Macedonian tombs are, present a specific interest so far as the conditions of their preservation are concerned. The excavation causes significant changes of the indoor microenvironment and results in accelerating the deterioration processes. The preservation of buried ancient constructions is achieved due to stable microclimate, insufficient oxygen and absence of bio-deterioration. "However, as soon as the excavation starts, the equilibrium is destroyed. Materials undergo deterioration processes when they are exposed to the aggressive action of the environment. The rate and symptoms of such processes are influenced by a number of variables, depending upon several environmental factors, acting separately or in various combinations". [2] "Where great changes do take place quickly on excavation, these are caused not by oxygen in the air neither by light, but by moisture change". [3] "Deterioration is mainly caused by cyclic changes of the air temperature and moisture inside the tomb chamber and outside". [4] These changes cause thermal and moisture fluxes through the mass of the stone walls.

Systematic monitoring of the micro-climate may lead to estimations about the factors which affect the stability of temperature and relative humidity conditions. After this process, appropriate interventions should be planned, in order to control the deterioration processes.

II. HERITAGE STRUCTURES – MACEDONIAN TOMBS

The Macedonian tombs are subterranean monuments of great importance, because they have been preserved since the 2nd - 3rd century B.C. Excavated in the area of Macedonia, northern Greece, they are built by large blocks of stone, with vaulted roof, having as a special characteristic the artificial covering by earth, named "tumulus". Most of them are preserved under stable microclimate in excellent condition. Their cultural value is high, as much as their educational value is.

2.1. Macedonian tomb D

A two-chamber tomb was excavated in Pella, being one of the largest Macedonian tombs up to now. [5] [6] It is believed to be the work of a local craftsman's workshop. Dated at the end of the 4th century B.C., it is built with local limestone and it has a temple-like front façade of Doric style. Fig. 1. The interior walls were depicted with architectural decorations and inscriptions from two different time periods. The tomb was covered by the large tumulus Fig. 2. It was preserved in a quite good condition, concerning the structural body. Fig. 3. A provisional wooden shelter was constructed in front of the tomb's façade, immediately after the excavation.

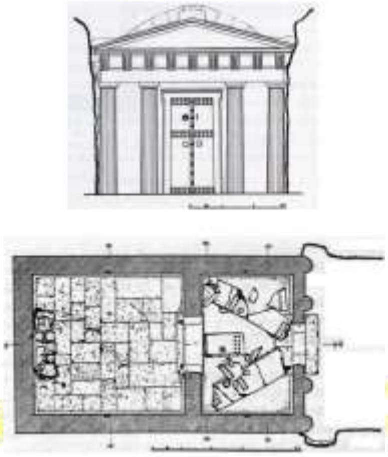

Fig. 1. Plan and front façade designs, Macedonian tomb D. [6]

Fig. 2. Tumulus over Macedonian tomb D.

Fig. 3. Macedonian tomb D - Front façade.

Geographically, tomb D is situated in the northeastern end of the plain of Thessaloniki, in the cove of the Thermaikos Gulf. The climate in the plain of Thessaloniki has the features of the Mediterranean climate. Air temperature has a simple fluctuation during the year, having the highest temperature in July and the lowest in January. Rain falls usually late in autumn and spring. Thus, during the winter and spring months there is a problem regarding the removal of the overflowing water and extreme moisture, but during the summer months, evaporation and drying procedures take place.

A systematic monitoring of the microclimate was conducted inside the burial chamber and the antechamber of the tomb, in different horizontal levels (ground level - middle level -upper level). Multiple groups of data were obtained (temperature and relative humidity), which were used as input to a simulation software. Fig. 4. Fig. 5. Fig. 6.

Fig. 4. Documentation. Digital censoring.

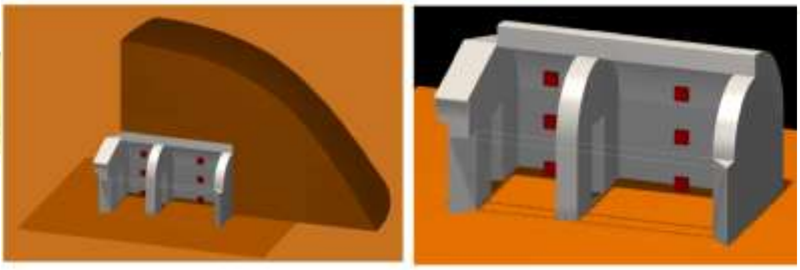

Fig. 5. 3D representation of the tomb. Positions of the sensors.

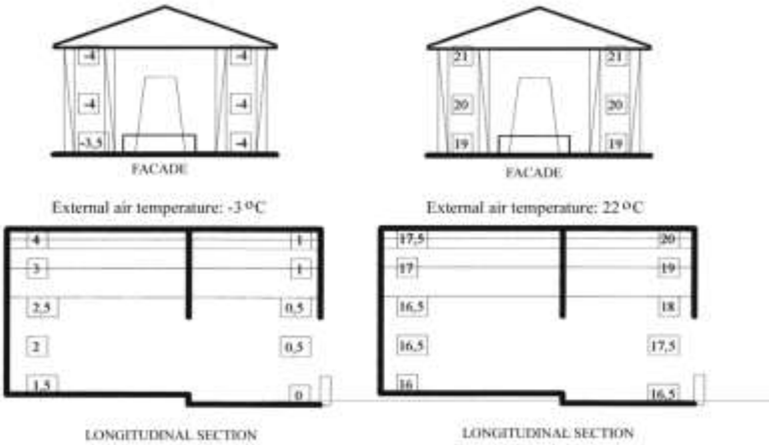

Fig. 6. Surface temperature data on the façade and the interior walls in winter and summer.

2.2. A comparison of the microclimate between the chambers and the environment.

The fluctuations of temperature and relative humidity were considerably different, compared to the outer climate. Inside the tomb-chambers there was a quite stable microclimate during the year, as diagrams show. Fig. 7. Fig. 8.

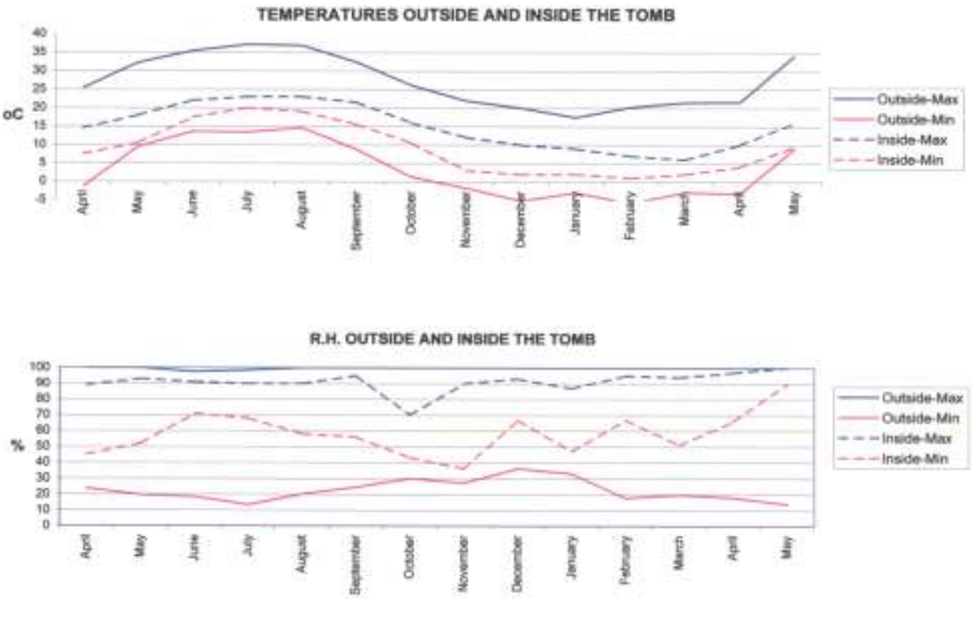

Fig. 7. Temperature and R.H. width of fluctuations during one year.

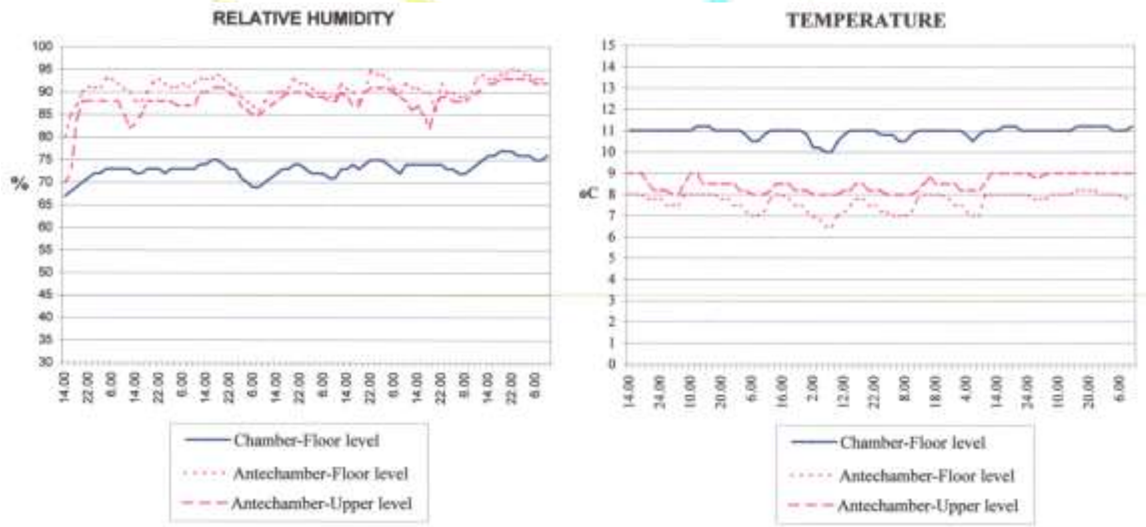

Fig. 8. Comparative diagrams showing temperature and R.H. at different positions of the tomb.

III. THE NUMERICAL SIMULATION

The simulation investigates the tombs' hygrothermal behavior, considering the local climatic conditions of Pella as well as the special characteristics of the building materials. It is based on realistic calculation of the transient hygrothermal behavior of multi-layer building components exposed to natural climatic conditions. [7] The results of the calculations are visualized. The simulation tool used in this study for the structural elements' hygrothermal performance analysis is the WUFI® 1Dpro. [8]

3.1. The equations

The WUFI® calculation program is based on heat and moisture transfer governing equations [9] which in one dimension are as follows:

$$\frac{\partial H}{\partial \vartheta}\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}(\lambda \frac{\partial \theta}{\partial x}) + h_v \frac{\partial}{\partial x}(\delta_p \frac{\partial p}{\partial x}) \qquad (1)$$

$$\frac{\partial w}{\partial \varphi}\frac{\partial \varphi}{\partial t} = \frac{\partial}{\partial x}(D_\varphi \frac{\partial w}{\partial \phi}\frac{\partial \varphi}{\partial x}) + \frac{\partial}{\partial x}(\delta_p \frac{\partial p}{\partial x}). \qquad (2)$$

In the above partial differential equations, θ stands for the temperature (K), $\frac{\partial H}{\partial \theta}$ is the heat storage capacity of the building material (J/kg), λ is the thermal conductivity, δ_p stands for the water vapor permeability, h_v is the evaporation enthalpy of the water, p is the water vapor saturation pressure, w stands for the moisture content, φ is the relative humidity and $\frac{\partial w}{\partial \varphi}$ is the moisture storage capacity.

3.2. Input data.

Input data were the following: the structural component, the respective material properties, the outdoor and the indoor climate, named as the boundary conditions.

3.2.1. Material data. The structural component of the facade.

The heat and moisture fluxes permeating the building component are not only determined by its present and past conditions and the boundary conditions, but also and foremost by the conductive and capacitive properties of the individual materials. There are basic data which are indispensable for a calculation. Other data may be optional, depending on the material and on the purpose of the calculation: Basic Material Data, Moisture Storage Function, Liquid Transport Coefficients, Heat Conductivity and Diffusion Resistance Factor. The study of simultaneous heat and moisture transfer inside natural stones is very complex, since there are many additional phenomena taking place, related to the shape and size of the voids and the properties of air inside the voids. [10]

Samples of stone and mortar from the tomb were analysed and the material properties were used as input to the simulation program, as follows.

The Tomb D was built with porous lime-stone, a local stone of Pella that was used in many buildings during the Hellenistic period. In the tomb's case, layers of lime-plaster (external and internal) cover the stone which have a thickness of 40cm.

So, the respective materials in this case study are lime-stone and lime-plaster, as in the following table.

TABLE. Material properties.

	Bulk Density	Porosity	Specific Heat Capacity (dry)	Thermal conductivity (dry) λ	Water Vapor Diffusion Resistance Factor μ-Value
	Kg/m^3	m^3/m^3	J/kgK	W/mK	[-]
Lime Plaster (internal)	1600	0.3	850	0.7	7
Limestone	2120	0.17	850	1.6	33
Lime Plaster (external)	1600	0.3	850	0.7	7

3.2.2. Climate Data

The analysis of the structural components' hygrothermal performance requires input data for the indoor and the outdoor climate. In this study, the weather data for the region of Pella were taken from the local meteorological station at Halkidona, which is situated close to the tomb, as in the following table.

TABLE. Input data for the outdoor climate.

Month	Air temperature (mean monthly values) (%)	Air relative humidity (mean monthly values) (ºC)
January	83,33	3,70
February	83,13	3,95
March	80,54	5,05
April	74,46	11,38
May	67,78	19,66
June	58,81	23,00
July	57,37	24,11
August	64,43	24,42
September	68,92	18,41
October	76,88	13,53
November	79,59	10,51
December	95,68	6,03

Multiple groups of data were obtained by the digital monitoring system. The following table presents the maximum, the minimum and the amplitude of temperature and relative humidity inside the tomb-chambers. These data were used as input to the simulation program, as in the following table.

TABLE. Temperature and relative humidity inside the tomb chambers.

Month	Air temperature (mean monthly values) (ºC)	Air relative humidity (mean monthly values) (%)
January	5,0	74,6
February	6,7	71,8
March	9,6	71,5
April	14,2	68
May	19,5	63,7
June	24,2	56,6
July	26,5	53,1
August	25,8	54,9
September	21,8	62,4
October	16,1	68,5
November	10,9	76,5
December	6,7	76,3

IV. RESULTS AND DISCUSSION

An interpretation of the numerical simulation results allows us to state the following:

1. Natural stone is a material having a wide range of hygrothermal parameters. As is shown in the calculations, porosity is an essential parameter of stone, because it is related to the maximum water content as well as to the suction and redistribution curves in the mass. The porosity determines only the absolute quantities and not the drying and water absorbing curves in relation to time (water content curves). The factor λ (thermal conductivity, a measurement of the ability of a material to transmit heat) seems to play an important role in the behavior of the natural stone.

2. The facade wall of the Macedonian tomb D’ is composed of three different material layers (external plaster - limestone - internal plaster) and presents a cyclic behavior during the year, characterized by water- absorbing periods and drying periods. A general estimate can be done using the total water content profile. During one year the water content of the wall changes periodically. Fig. 9, Fig. 10.

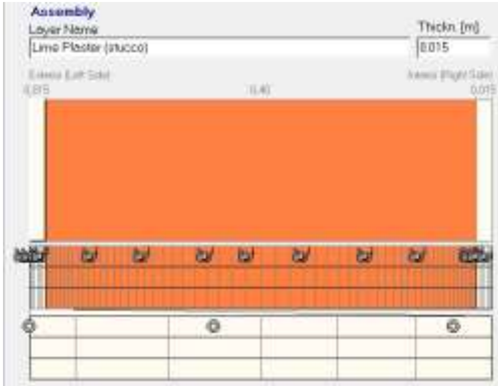

Fig. 9. The façade structural component and the monitoring positions inside the mass, visualized in the simulation software.

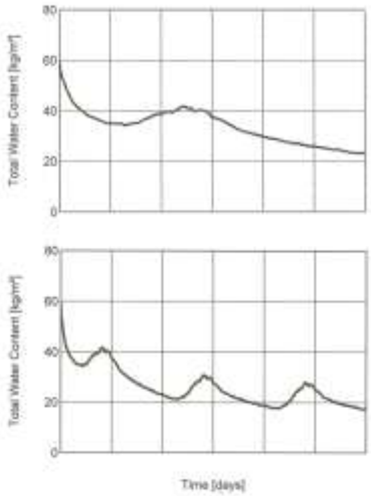

Fig. 10. Total water content of the facade structural component during the first year after the excavation and during three years.

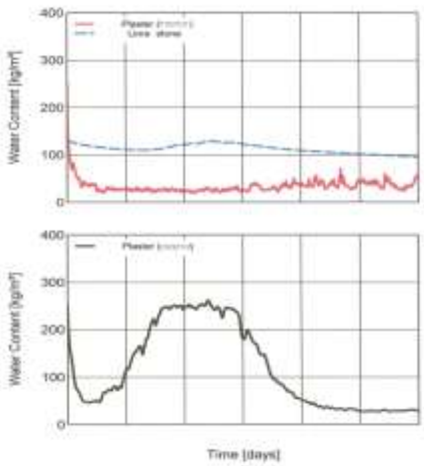

Fig. 11. Water content of the facade structural component in each of the three material layers of the tomb façade: internal plaster – stone – external plaster.

3. Comparative diagrams of temperature and water content during one year at different monitoring positions of a cross section of the tomb's structural component show that there is a quite different behavior if the water content is examined in each of the three material layers of the tomb façade. Fig. 11.
4. Comparative diagrams show that the width of the temperature fluctuation in the facade wall is getting larger from the inner layer to the outer. The water content is quite stable inside the stone mass, but presents an intense fluctuation on the two boundary layers. The water-absorbing and drying procedures make the external layer of lime plaster the mostly vulnerable to periodical changes. Fig. 12. Fig. 13.

Fig. 12. Temperature in different monitoring positions of the façade structural component during one year.

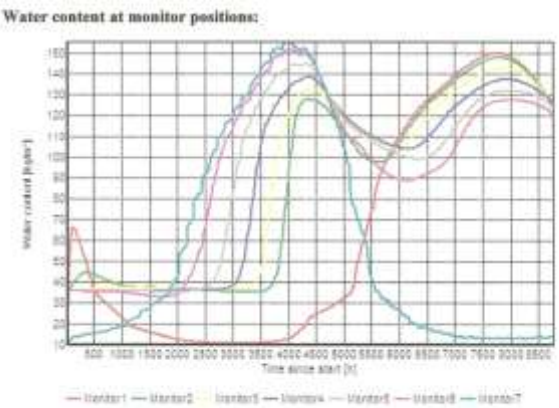

Fig. 13. Water content in different monitoring positions of the façade structural component during one year.

5. The one-year diagram of temperature and dew point inside the stone mass, shows the possible condensation period. Fig. 14. This period is determined by the distance of the two curves in the diagram. Condensation occurs when the temperature of the air inside the pores of the material is lower than the dew-point temperature.

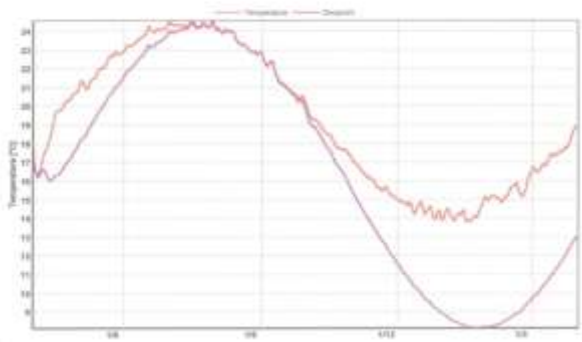

Fig. 14. One year diagram: temperature and dew-point inside the stone mass.

6. During condensation period, there should be additional provision to protect the Macedonian tombs. The temperature and relative humidity levels need to be controlled in order to eliminate the possibility of condensation. During the drying periods, the drying rate of the surface plasters should also be controlled, in order to avoid the exfoliation and loss of important wall painting decorations.

V. CONCLUSIONS

The conclusions indicated by this study can be summarized as follows:

1. The structural component of the tomb's façade is mostly vulnerable to periodical changes of the outdoor climate conditions.
2. The structural component's total water content curve shows that there is a drying course during the months following the excavation. The materials never get back to the initial water content status at the time of excavation.
3. As far as the internal and external plaster is concerned, different behaviors are observed. Profiles of the three layers of the façade construction (external plaster - limestone - internal plaster) show that the internal plaster presents smooth curves, opposite to the external, where the changes are intense. If we consider the fact that the plaster covering a Macedonian tomb's façade is often the supportive layer for wall decorations, these cyclic changes are very dangerous, leading to deterioration processes. The great vulnerability of the façade's structural component has to be assessed.
4. The structural component's total water content curve shows that after the excavation the drying procedure is very intense during the first period (April-June), after which starts the opposite phenomenon, until September. Until the end of the first year it is not clear enough what will follow. In order to achieve a clear view of the structural components' behavior, i.e., the so-called "dynamic balance state" it is important that the calculation period must have a three year's duration.
5. It is interesting to observe the dew-point curve in relation to the temperature curve. There are specific periods of the year during which the condensation risk is very high. This is when the two curves are too close one to another. That happens due to thermal inertia during the hot months (summer condensation) and during the cold months of the year (winter condensation).
6. The hygrothermal behavior of the tomb façade depends mainly upon the boundary climatic conditions and can be changed by controlling the microclimate.

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