

DETERMINATION OF DEFORMATIONS OF THE ANCIENT TEMPLE OF ZEUS IN NEMEA, GREECE

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Abstract: In this paper the determination of the deformations of the crepis of the ancient temple of Zeus in Nemea is presented. For this purpose a horizontal and a vertical control network were established in the vicinity and on the body of the temple, and the actual inclinations as well as the positions of the orthogonal stones of the temple's crepis were determined. Significant horizontal and vertical displacements were detected mostly due to ground settlements all over the centuries as well as to human activity [6]. The best fit lines of the four sides of the most important surface of the crepis (the temple's floor) were determined, using least squares techniques, and were compared to those proposed by the responsible of the restoration works. The subsidences of the sides of the crepis were also determined through the comparison of the actual inclinations against the original ones.

1. INTRODUCTION

Deformations of ancient monuments are due to various causes of either natural (earthquakes, ground movements or even storms) or human effect. It is well known that most of the public ancient monuments, such as theatres or temples were constructed on the basis of strict plans demanding high accuracy in construction and workmanship of high qualification. Many cases of investigations concerning deformations of ancient monuments have therefore as a purpose to contribute to the restoration of the monument in its original form, providing all necessary information.

2. THE ANCIENT TEMPLE

The sanctuary of Zeus in Nemea developed at the beginning of the 6th century B.C., with the institution of the Panhellenic Nemean Games in an area where human activity had been present since prehistoric times. The first temple of Zeus was constructed during the first part of the 6th century, probably around the start of the biennial games in 573 B.C. This temple was destroyed in the late 5th century, together with most of the monuments of the sanctuary, during the Peloponnesian war, and the Nemean Games were transferred to Argos, a city nearby. About 330 B.C. a new temple of Zeus, together with baths, a hostel and a Stadium

were built as part of a large construction project. The construction of the new temple is the proof of the return of the Games back to Nemea, probably as a consequence of the strategy of the king of Macedonia, Philippos, and his son Alexander, who used the great panhellenic games as a mean for the union of Greek people.

The new temple of Zeus was constructed over the remnants of the first one [4]. One of its main characteristics is that the exterior columns, three of which survived in situ, are quite slender, thus indicating the progress of the Greek architecture from Classic to Hellenistic forms. The temple had an exterior colonnade with 6 columns on the short sides and 12 (rather than the Classical 13) on the long ones. The eastern façade was equipped with an approach ramp, which is characteristic of the period. The rear porch (*opisthodomos*), typical of the Doric temple, does not exist, and is substituted by a sunken crypt (*the adytum*), at the back of the cella, and was approached by stone stairs. This crypt was probably the site of a local oracle, possibly Opheltes. The interior of the temple had a Corinthian colonnade at the three sides of the cella. An Ionic colonnade stood above the Corinthian one, so that all the three architectural orders were present in the temple.

After the transfer of the games once again in Argos a long period of decline began. Pausanias, who visited the site about 150 A.D. saw the temple abandoned, its roof thrown down and the worship statue missing. During the 5th and 6th centuries a small community grew in the ruins of the sanctuary. This community erected a Basilica in a place about 100m south of the temple. This is the time when the systematic demolition of the temple of Zeus began, in order to use its elements for the construction of the church. The external Doric columns were knocked down and about 1300 parts of the temple were removed. The Corinthian columns were used in the interior of the new church. As it has been mentioned above only 3 of the 36 Doric columns remained in place. The Christian community was dissolved during the raids of Slavs in 580 – 590 A.D.

The first visitors of the modern times arrived in Nemea about the second half of the 18th century. They found a deserted valley dominated by the 3 columns. The ruins of the temple were surrounded by the fallen column drums, staying there, unused, for centuries. Excavations in the area began in 1766, were continued in 1884 till 1912 by the French school of Archaeology in Athens. During the years 1924 – 1926 investigations were carried out by the American School of Classical studies. Finally, extensive and systematic excavations on the site and partial restoration of the Temple were carried out by up till nowadays by the University of Berkeley in California, under the direction of Prof. S. Miller [1].

The restoration works on the temple of Zeus began in 1984. A year later, 42 stone blocks of the foundations were put back in their place [7]. The gaps of the lost members were filled with new stone blocks. However, due to lack of funds, the works were suspended for 15 years. They were continued in 1999 and in 2002 two of the fallen columns were restored with their architrave.

In 2004 a new restoration project began in order to complete the northeastern part of the peristyle of the temple. Four more columns are going to be reconstructed using identified drums of the fallen columns as well as their epistyles [9]. For this purpose it was decided to investigate both the horizontal and vertical displacements of the crepis. These displacements are due to human destruction (mostly in the early Christian period) as well as to settlements since the foundation of the temple is not on solid mass.

3. THE GEOMETRY OF THE CREPIS

The crepis of ancient temples - *Crepis or crepidoma: the stepped platform of a Greek Temple* [2] - consists of four different surfaces: the *euthynteria* - the Greek term for the special top

course of the foundation used as a leveling course [2] -, the 1st and 2nd steps and the stylobate, all four of which are situated above the foundation. From the etymology of the word *euthyneria*, as well as from its meaning, it can be seen that the surface of the euthyneria is the one that imposes the shape of the monument's floor, defining the basic lines and dimensions of the temple. All the other surfaces of the crepis are produced through inward parallel movements of the sides of the euthyneria. Moreover all the surfaces that consist the crepis are not horizontal but curved ones, with different transversal and longitudinal gradients. These outwards inclinations facilitated the shedding away of the rainwater, and in their turn they are related with the inclinations of the columns. The curvatures and the inclinations consist the famous refinements of the ancient Greek Temples [8], [2], [1], [10]. It must be also pointed out that usually, the four angles of the crepis surfaces were not at the same level [2].

Professor N. Makris, director of the project, set us, in name of the University of California, Berkeley, which is responsible of the excavation works in the archaeological site of Nemea, to determine the existing geometry of the euthyneria, using geodetic methodology, following, through analysis, estimate the original geometry (shape and dimensions) and, finally, by comparing the existing against the estimated initial conditions, determine its deformations, both horizontal and vertical ones.

4. THE GEODETIC CONTROL NETWORKS

4.1. Horizontal control network

An horizontal control network, consisting of reference (S_1, \dots, S_{10}) and control points, was established in order to determine the horizontal displacements of the temple's euthyneria [3]. Five reference points (S_1, S_2, S_3, S_4, S_5) were established in the vicinity of the monument, while reference points (S_6, S_7, S_8, S_{10}) were established on the body of the temple in order to ensure their stability (Figure 1). The control points were established on the faces of the stones of the euthyneria, two points on each stone in especially selected positions indicated by the responsible of the restoration works. They were marked by notching a small cross, so that they could be used, if necessary, in the future.

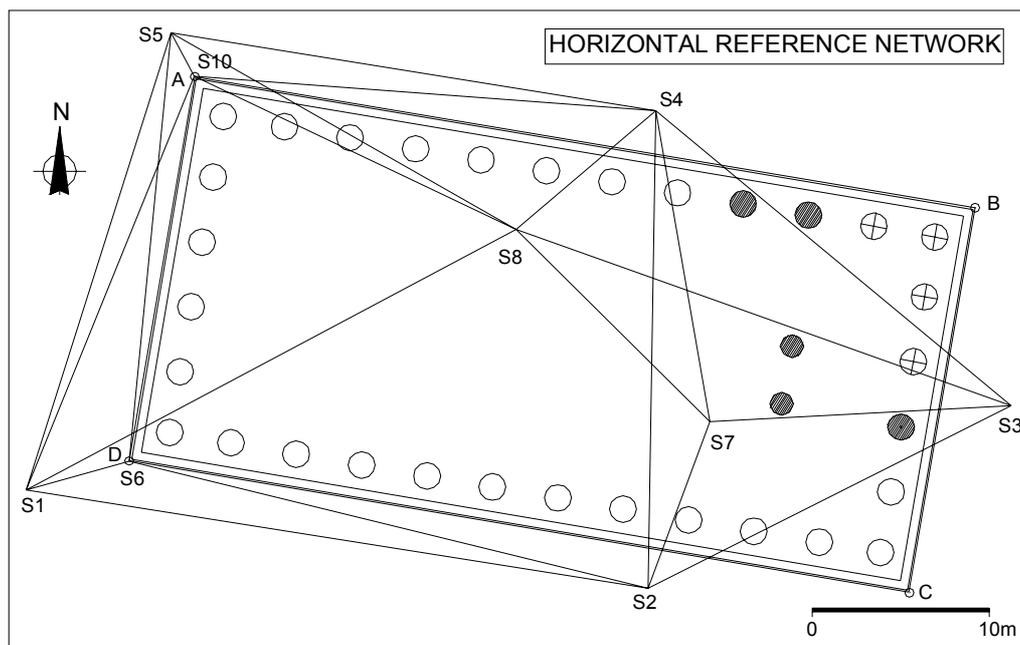


Figure 1: The horizontal reference network

Angle (horizontal and vertical) and distance measurements were carried out between the reference points, as well as between the reference and the control points of the network. The observations were carried out with the total station TC1600 WILD, having an accuracy of $\pm(3mm + 2ppm)$ in length measurements and $\pm 0.3mgon$ in angle measurements. The instrument was tested in laboratory before the field campaign in order to eliminate the possibility of the existence of systematic errors in the observations, due to incorrect instrument function.

The angles (horizontal and vertical) between the reference points were observed in two full sets, distances were measured from both ends of the line, while lines and angles (horizontal and vertical) between the reference and the control points were measured in one set.

The observations between the reference points of the network consisting of 21 distances and 25 horizontal angles, were adjusted by Least Squares, using the minimum external constraints: the coordinates of reference point S_8 and the azimuth of side S_8-S_7 , were kept fixed ($X_{S_8} = 1000m$, $Y_{S_8} = 1000m$ and $\alpha_{S_8,S_7} = 150^\circ$) in a local, arbitrarily chosen reference coordinate system. The null hypothesis was accepted from the global test (χ^2 - test) applied on

the a posteriori standard deviation of the unit weight $\hat{\sigma}_0 = \pm 1.07$, while no observation was rejected when Baarda's data snooping was applied for outlier detection.

The estimates of the coordinates (X, Y) of the horizontal network reference points, along with their standard deviations are depicted in Table 1. Following the coordinates (X, Y) of the network's control points were estimated in the same reference system [3].

No	CODE	X (m)	σ_X (mm)	Y (m)	σ_Y (mm)
1	S ₁	972.341	± 2.3	985.147	± 2.3
2	S ₂	1007.431	± 1.5	979.574	± 1.8
3	S ₃	1027.928	± 2.5	989.941	± 1.3
4	S ₄	1007.864	± 1.1	1006.762	± 0.7
5	S ₅	980.524	± 2.1	1011.170	± 1.5
6	S ₆	978.144	± 2.7	986.801	± 2.2
7	S ₁₀	981.827	± 2.1	1008.705	± 1.8
8	S ₇	1010.936	± 1.1	989.064	± 1.1
9	S ₈	1000.000	0.0	1000.000	0.0

Table1: Coordinates and standard deviations of the network's reference points

4.2. The Vertical Control Network

The vertical control network consisted of the reference points of the horizontal network (S₁, ..., S₁₀) and the vertical control points which were marked the horizontal ones on the upper sides of the euthynteria, two points on each stone. The height differences between the reference points of the network were observed by double run leveling. The digital level NA3000 WILD having a precision of $\pm 1mm / \sqrt{km}$, in combination with bar-coded rods, was used for the observations. The instrument was tested before and after the field campaign.

15 height differences between the reference points were determined and the heights of the reference points of the network were estimated by Least Squares adjustment, with the minimum external constraints: the height of reference point S₈ was kept fixed ($H_{S_8} = 100m$). The null hypothesis was accepted from the post adjustment global test and no observation was

rejected when data snooping was applied. The adjusted heights of the network's reference points together with their standard deviations are depicted in Table 2.

No	CODE	H (m)	σ_H (mm)
1	S ₁	98.151	± 0.4
2	S ₂	99.012	± 0.3
3	S ₃	98.497	± 0.3
4	S ₄	98.631	± 0.3
5	S ₅	97.666	± 0.4
6	S ₆	98.449	± 0.4
7	S ₁₀	98.396	± 0.3
8	S ₇	99.963	± 0.3
9	S ₈	100.000	0.0

Table 2: Heights and standard deviations of the network's reference points.

The height differences between the reference and the control points of the network were, following, determined by single leveling using the same, as above, instrumentation. Using the adjusted heights of the reference points the heights of the control points of the vertical network were estimated [3]. Using these heights the profiles of the four sides of the euthynteria were plotted, in order to determine the actual inclinations of each side (Figure 2).

5. ESTIMATION OF THE DISPLACEMENTS

The problem in estimating displacements of the parts of ancient monuments generates from the fact that the original geometry of the building is not known. Therefore one must estimate the original "as built" geometry (shape and dimensions), taking into account previous investigations in other ancient buildings, and determine the deformations through the comparison of the estimated original geometry with the existing one.

The plan of the euthynteria has the form of an orthogonal parallelogram therefore, in order to determine its initial dimensions, the equations of four lines must be determined. Thus for each side the line that fits best the control points must be estimated using as observations the coordinates of the control points of the horizontal network that belong to this side. In order to decide which control points should participate in the adjustment, the line joining the two ends of each side was drawn and the control points that lie outside this line were rejected. Moreover the control points, lying on stones where vertical displacements are observed from the plotted profiles, were also rejected.

For the i control point of each side the following observation equation is formed:

$$a \cdot x_i + b - y_i = 0 \quad (1)$$

where: a , b : the coefficients of the line, treated as the unknown parameters,

x_i , y_i : the point's coordinates treated as the observations in the adjustment.

If i is the number of the control points that participate in the adjustment, then the number n of the observations is $n = 2 \cdot i$, the number of the parameters to be estimated is 2 (the coefficients of the line), the number m of the parameters involved in the adjustment is $m = i + 2$, the number c of the condition equations that hold between the parameters to be estimated and the observations is $c = n - m + 2$, and the degrees of freedom are $r = n - m$.

Since equation (1) is not linear with respect to the parameters and the observations, it is approximated by a linear Taylor series, and becomes:

$$x_i \cdot \delta a + \delta b + a^0 \cdot v_{x_i} - v_{y_i} = y_i - a^0 \cdot x_i - b^0 = w \quad (2)$$

where : a^0, b^0 : the approximate values of the parameters,

v_{x_i}, v_{y_i} : the residuals of the observations.

Thus, the linearized mathematical model, in matrix form, is [5]:

$$A \cdot \hat{\delta} + B \cdot \hat{v} = w \quad (3)$$

$$\text{with : } A_2^i = J(\hat{\delta}) = \begin{bmatrix} x_1 & 1 \\ x_2 & 1 \\ \vdots & \vdots \\ x_i & 1 \end{bmatrix} \quad (4)$$

$$B_n^c = J(\hat{l}) = \begin{bmatrix} a^0 & -1 & 0 & 0 & \dots & 0 \\ 0 & 0 & a^0 & -1 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \dots & a^0 & -1 \end{bmatrix} \quad (5)$$

$$\hat{\delta} = \begin{bmatrix} \delta a \\ \delta b \end{bmatrix} \quad (6)$$

\hat{v}_1^n : the residual vector, and

w_1^i : the misclosure vector.

From equation (3) the system of normal equations is derived and the vector $\hat{\delta}$ of the estimates of the adjustment is determined:

$$\hat{\delta} = \left(A^T \left(B \cdot P^{-1} \cdot B^T \right)^{-1} A \right)^{-1} A^T \left(B \cdot P^{-1} \cdot B^T \right)^{-1} w \quad (7)$$

where : $P^{-1} = \sigma_0^2 \cdot V_l$, and

V_l : is the variance –covariance matrix of the control points' coordinates. By applying the law of error propagation it was assumed that $\sigma_{x_i} = \sigma_{y_i} = \pm 5mm$, and thus V_l is a diagonal matrix.

The vector of the residuals is also determined through the equation:

$$v = P^{-1} \cdot B^T \cdot \left(B \cdot P^{-1} \cdot B^T \right)^{-1} (w - A \cdot \hat{\delta}) \quad (8)$$

and the adjusted values of the points' coordinates are estimated.

Finally the a posteriori variance of the unit weight $\hat{\sigma}_0^2$ and the a posteriori variance – covariance matrix of the estimated parameters, $\hat{V}_{\hat{x}}$ are determined:

$$\hat{\sigma}_0^2 = \frac{v^T \cdot P \cdot v}{r} \quad (9)$$

$$\hat{V}_{\hat{x}} = \hat{\sigma}_0^2 \cdot \left(A^T \cdot (B \cdot P^{-1} \cdot B^T)^{-1} \cdot A \right)^{-1} \quad (10)$$

The following results were obtained from the four independent generalized least squares adjustments, one for each side of the euthynteria.

- Northern side

From the 42 control points situated on the stones of the northern side, 20 were used in the adjustment for the estimation of the line's coefficients, since the rest lie on stones where significant vertical displacements were observed. The best-fit line is given by the equation:

$$y = -0.16956 x + 1175.172$$

- Southern side

All the control points (34 as a whole) participated in the adjustment. The best-fit line is given by the equation:

$$y = -0.17036 x + 1153.448$$

- Eastern side

19 control points, from the total 22, were used for the estimation of the line's coefficients. The best-fit line is given by the equation:

$$y = 5.90932 x - 5061.169$$

- Western side

All of the 19 control points were used for the estimation of the line's coefficients. The best-fit line is given by the equation:

$$y = 5.1421 x - 4798.160$$

From these equations, the coordinates of the points of intersection of every two adjacent lines were determined (Table 3). These points represent the four corners of the orthogonal parallelogram that approximates in a best-fit way, the original geometry of the euthynteria.

POINT	X (m)	Y (m)
A	981.847	1008.691
B	1025.903	1001.221
C	1022.195	979.308
D	978.148	986.813

Table 3: Coordinates of the points of intersection of the adjacent best-fit lines.

In order to investigate the goodness of fit of the estimated orthogonal parallelogram the following geometric features were determined and compared to those given by the responsible of the restoration [9] (Table 4).

ESTIMATED		RESTORATION		DIFFERENCES	
SIDE LENGTHS	ANGLES	SIDE LENGTHS	ANGLES	IN LENGTH	IN ANGLE
AB = 44.685m	A = 99.970g	AB = 44.692m	A = 99.936g	- 7 mm	+ 3.4 ^c
BC = 22.225m	B = 100.021g	BC = 22.205m	B = 99.929g	+ 20 mm	+ 9.2 ^c
CD = 44.682m	C = 99.928g	CD = 44.645m	C = 100.033g	+ 37 mm	- 10.5 ^c
DA = 22.188m	D = 100.081g	DA = 22.179m	D = 100.101g	+ 9 mm	- 2.0 ^c

Table 4: Comparison of the geometric features of the euthynteria.

As it can be seen from the first two columns the differences between the lengths of the opposite sides of the parallelogram range from 3mm (for the long sides) up to 37mm (for the short ones), while their departures from perpendicularity does not exceed $\pm 8^{\circ}$. Differences between the features of the two parallelograms are of the same range. These differences, which are approximately 1/3200 to 1/6400 of the lengths, lay within the accuracy of construction, which is a function of the material used, the workmanship qualification and the importance of the monument, and, according the responsible of the restoration works, is of this magnitude for the crepidoma [9].

Horizontal displacements ranging up to 3cm were observed in the northern and eastern side of the euthynteria. Their magnitude was estimated from the comparison between the estimated original geometry and the existing one.

The curvature of the euthynteria surface can be observed from the plotted vertical profiles of the four sides (Figure 2). Although the four corners of the surface are not situated on the same level, significant vertical displacements are observed especially in the northwestern part of the euthynteria, their magnitude ranging up to 57mm. These displacements can be explained from the fact that the banks of the Nemea's river are located just next to the temple, and that the temple's foundation is not on solid mass.

6. CONCLUSIONS

From our investigations it is shown that the geometric features of the crepidoma of the temple can be approximated by analytical methods such as line equations, using least squares techniques for the coefficients estimation. The differences between the geometric features determined analytically and those determined by the responsible of the restoration are within the overall accuracy of the crepidoma's construction.

Special care must be taken in the selection of the position of the horizontal and vertical control points: they should be established on stones of the crepidoma whose surface shows no indications of destruction or corrosion. Their number and distribution must ensure the reliable documentation of the crepidoma characteristics. The points, which are selected to be used for the determination of the lines features, must be those established on stones that prove no apparent signs of deformation.

It is useful to establish at least two reference points on the crepidoma body, in order to ensure the permanence of the reference system throughout the works of the restoration.

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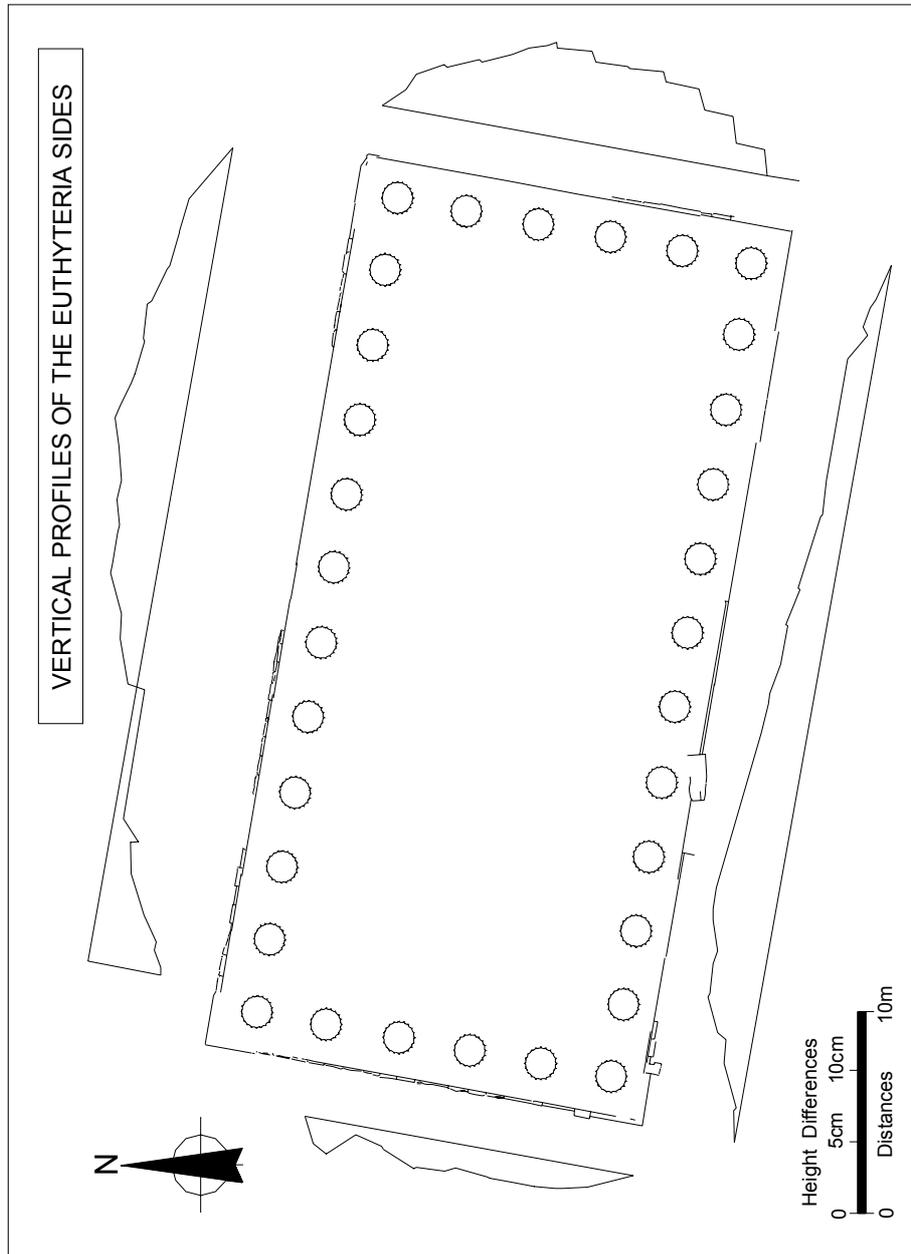


Figure 2: The vertical profiles of the euthyteria sides

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