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Impermeation of Macedonian Tombs in N. Greece using grouting techniques.

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ABSTRACT

In the present paper a grouting technique was studied in order to protect the buried monuments against the presence of the ground water. The Macedonian Tombs of N. Greece were used as a pilot example for study, given that they are buried in loose sediments where the aquifer overflows their floors. Although the proposed method is expensive, it establishes permanent drainage conditions regarding to pumping. The purpose of this method is to create an impervious shell, which isolates the floor and the walls of the tombs, so as the monuments to be impervious. In this paper the type of the chemical grout as well as the length and the number of necessary boreholes were calculated taking into account the penetration of the grout and the orientation of the boreholes. The number of the boreholes that is needed to impermeate the building that includes the Krisis tomb is 46 and for the Krisis tomb is 24. The total length of boreholes for the first case is 750,54m and for the other one is 297,62m. The grout mixes are colloidal solutions or polymers such as silica or ligno chrome gels, tannins, organic colloids on polyurethane, or pure chemical solutions such as acrylamides, aminoplast or phenoplast, depending the grain-size changes of the soil.

Key words: Monuments, grouting, impermeation, drainage.

A. DESCRIPTION OF TOMBS AND GEOLOGICAL SETTINGS

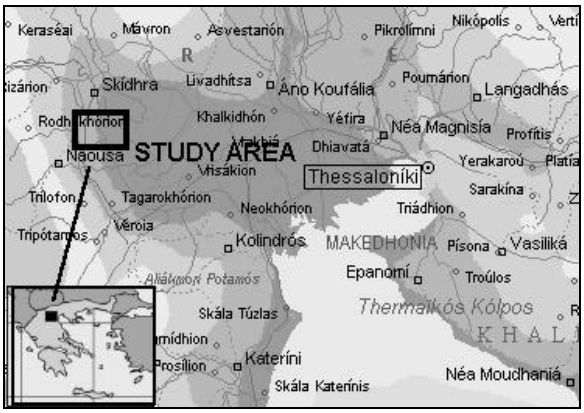

Figure 1: Location map of the study area.

The Macedonian Tombs of the area were located between Kopanos and Lefkadia villages, on the national road connecting Veroia with Skidra and Edessa Cities, in Northern Greece (Fig. 1). These monuments are of the 3rd c. B.C. and contain frescos

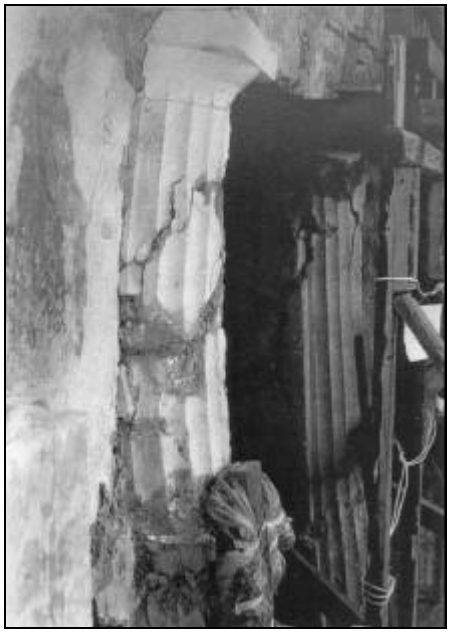

Figure 2: The facade of the Krisis Tomb presents significant damages.

of significant importance. This kind of Tombs was used for burying members of the King family or other important members of the Macedonian Kingdom of that period. The tombs were constructed using big block of travertine, which are very abundant in the area. These tombs are now buried in the soil, due to the sedimentation.

In the present paper, the Tombs of Krisis, Anthemion and Lysson & Kallikles are investigated by geotechnical and hydrogeological point of view. The facades and the walls of the tombs are covered by frescos, which are influenced by the high inside humidity conditions. The monuments also present important weathering and stability (differential settlement phenomena) problems (Fig. 2).

Geologically, the area is located in the western part of Almopia zone (Kilias & Moundrakis, 1989). The surrounding area of the Tombs is consisted of resent alluvial deposits with fans and telus cones as well as Pleistocene lacustrine and continental deposits, with clay, loam, sand, conglomerates and travertine (IGME, 1982). The thickness of these deposits is estimated about 100 m and increases up to 200-300 m to the east.

B. HYDROGEOLOGICAL SETTINGS AND GEOTECHNICAL CONDITIONS

The reservoir of the rivers and aquifers of the study area is the mountainous limestone masse located to the West of the Tombs (Vermio Mountain), (Athanasias & Soulios, 1995). Four boreholes (G_1-G_4, depth: 20 m) were constructed in order to investigate the geotechnical and hydreogeological features of the soil (Krisis Tomb: G_1, G_2, Anthemion tomb: G_3 and Lysson & Kallikles Tomb: G_4), (Christaras et al., 1997).

According to the borehole data, the formations in which the Tombs are buried are consisted of alluvial deposits with clay, sand, gravel and conglomerates. The soil materials are generally loose and coarse grained, presenting, active porosity and permeability that vary depending on the grain size distribution of the soil. The core recovery value also varies regarding to the grain size and the cohesion of the soil materials.

The depths of the groundwater level in these four boreholes, measured once a month, give the following values: G_1 = 7.30-8.26, G_2 = 7.00-7.95, G_3 = 6.97-8.05 and G_4 = 4.56-4.92. The ground level is practically horizontal. The difference of the water levels in the above boreholes determines an eastward water flow direction, related to the limestone of Vermio mountain, located to the West of the study area. The hydraulic gradient has estimated 12-14%.

The foundation levels of the Tombs are lower than the water table in the area. So, the groundwater overflows the floors of the monuments causing damages related to a) the weathering of the walls and frescos and b) differential settlements and instability of the construction (Fig. 3). The depth of the groundwater table is not constant during the year but increases during summer, when irrigation activities start. During this period a big quantity of surface water enrich the aquifer rising the water table. For this purpose, the main problem of our study is to find out a reasonable way to protect the tombs from the presence of the underground water.

Figure 3: Krisis Tomb. The differential settlement caused failures and displacements on the front wall.

C. IMPERMEATION GROUTING TECHNIQUE

Impermeation grouting technique tries to be applied as a proposed method for establishing permanent drainage conditions regarding to pumping. The purpose of this method is to create an impervious shell, which isolates the floor and the walls of the tombs. Thus, all the walls of the tomb are achieved to be impervious.

According to the borehole data, the most suitable grout is estimated for every geological formation and the radius of grout.

Table 1. Estimation of the type of grout for the Krisis Tomb

Borehole	Depth (m)	D_{10} (mm)	Permeability of soil (cm/sec)	Type of grout	Strength & Permeability data after grouting	Investigator
G1	3.00-3.40	0.0015	$2.25 \cdot 10^{-6}$	Resin grouted sand AM-9	q_u=1242psi $ó_1$-$ó_3$=1230psi	Graf, 1982
>>	5.0-6.2 6.5-7.0	0.013	$2.25 \cdot 10^{-4}$	Resin grouted sand AM-9	q_u=1242psi $ó_1$-$ó_3$=1230psi	Graf, 1982
G2	5.60-7.00	0.15	$1.56 \cdot 10^{-2}$	Silicate grouted sand Aluminate+Amide	q_u=239psi $ó_1$-$ó_3$=177psi	Graf, 1982
	7.00-8.45				q_u=280psi	Karol, 1968
>>	9.60-13.0	0.85	$8.1 \cdot 10^{-3}$	Resin grouted sand Chrome Lignin		Karol, 1982
>>	13.0-14.0	0.095	10^{-2}	Silicate grouted sand Aluminate+Amide	q_u=280psi	Karol, 1968
>>	15.0-15.6	0.13	$1.96 \cdot 10^{-2}$	Silicate grouted sand Aluminate+Amide	q_u=280psi	Karol, 1968

The first estimation of the grout mix is based on the D_{10} of the grain size distribution. So, if D_{10} varies between 0.02mm and 0.5mm, colloidal solutions or polymersis used, such as silica or lignochrome gels, tannins, organic colloids on polyurethane. If D_{10} is less than 0.02mm, pure chemical solutions are used such as acrylamides, aminoplast or phenoplast.

Another estimation of the grout mix is based on the permeability of the soil. Thus, if the permeability is 10^{-4} cm/sec an acrylamide based grout is used. The viscosity of grout is less than 2cp. If the permeability is higher than 10^{-3}cm/sec, chrome lignin and phenoplast is used. The viscosity of grout is 5cp. If the permeability is higher than 10^{-2}cm/sec, a silicate-based grout with viscosity 10cp or a simple grout mix can be used.

When the two estimations are completed, the most suitable grout is chosen according to the tables of Shroff & Shah (1993). The main characteristics of the strength and permeability of the grouts, and the soil where grouting will be applied, are mentioned in these tables. So, the more suitable grout can be chosen, according to the kind of the soil and the two previous estimations.

Table 2. Calculation of the radius of grout for the Krisis Tomb

Borehole	Depth (m)	Injection head h (cm)	Porosity n (%)	Radius of injection pipe r (cm)	Time t (sec)	Ratio of viscosity of grout to that of water a	Radius of grout R (cm)
G1	3.00-3.40	800	5	2.5	2100	2	6.45
>>	5.0-6.2 6.5-7.0	1400 1700	5	2.5	2100	2	36.74 39.2
G2	5.60-7.00	1600	25	2.5	2100	10	53.97
	7.00-8.45	1805					56.19
>>	9.60-13.0	2200	10	2.5	2100	5	82.49
>>	13.0-14.0	2700	10	2.5	2100	10	75.2
>>	15.0-15.6	2940	20	2.5	2100	10	76.84

The next stage of our method is to calculate the radius of the grout as to calculate the distance of each grouting and the exacted number of groutings. The radius of the grout is given by $t = (an/3khr)(R^3-r^3)$(Raffle & Greenwood, 1961), where k = soil permeability (m/sec), h = injection head (m), t = time (sec), r = radius of source (m), R = Radius of grout at time (m).

The example of the Krisis Tomb(3rd c. B.C.)

It is one of the most important Macedonian Tombs. On the principal facade of two floors, the Ionic style is alternated with the Doric one.

According to the borehole data, at the depth from 5.6 m to 15.6 m where D_{10} depends from 0.02 mm to 0.5 mm the most valuable grout mixes are colloidal solutions or polymers such as silica or ligno chrome gels, tannins, organic colloids on polyurethane. At the depth from 3 m to 7 m where D_{10} is less than 0.02 mm the most valuable grout mixes are pure chemical solutions such as acrylamides, aminoplast or phenoplast. At the depth from 5 m to 7 m, where the permeability is 10^{-4} cm/sec, it is better to use grout based on acrylamide. The viscosity of grout is 2 cp. At the depth from 5.6 m to 8.45 m and from 13 m to 15.6 m, where permeability is higher than 10^{-2}

Table 3. Length of boreholes for A) the building which includes the tomb and B) the tomb.

A

A/A	I	II	III	IV	V	VI	VII	VIII
Length (m)	25.88	27.29	25.81	24.04	22.27	20.51	18.81	17.04

A/A	IX	X	XI	XII	XIII	XIV	XV	XVI
Length (m)	15.27	13.58	11.74	11.03	11.03	11.74	13.58	15.27

A/A	XVII	XVIII	XIX	XX	XXI	XXII	XXIII	XXIV
Length (m)	17.04	18.81	20.51	22.27	24.04	25.81	27.29	25.88

A/A	XXV	XXVI	XXVII	XXVIII	XXIX	XXX	XXXI	XXXII
Length (m)	27.29	25.74	23.97	22.2	20.36	18.53	16.83	15.06

A/A	XXXIII	XXXIV	XXXV	XXXVI	XXXVII	XXXVIII	XXXIX	XXXX
Length (m)	13.29	11.45	11.03	11.03	11.45	13.29	15.06	16.83

A/A	XXXXI	XXXXII	XXXXIII	XXXXIV	XXXXV	XXXXVI
Length (m)	18.53	20.36	22.2	23.97	25.74	27.29

B

A/A	I	II	III	IV	V	VI
Length (m)	19.44	17.54	15.77	13.79	11.88	11.03

A/A	VII	VIII	IX	X	XI	XII
Length (m)	11.03	11.88	13.79	15.77	17.54	19.44

A/A	XIII	XIV	XV	XVI	XVII	XVIII
Length (m)	18.88	17.18	15.48	13.79	12.09	11.03

A/A	XIX	XX	XXI	XXII	XXIII	XXIV
Length (m)	11.03	12.09	13.79	15.48	17.18	18.88

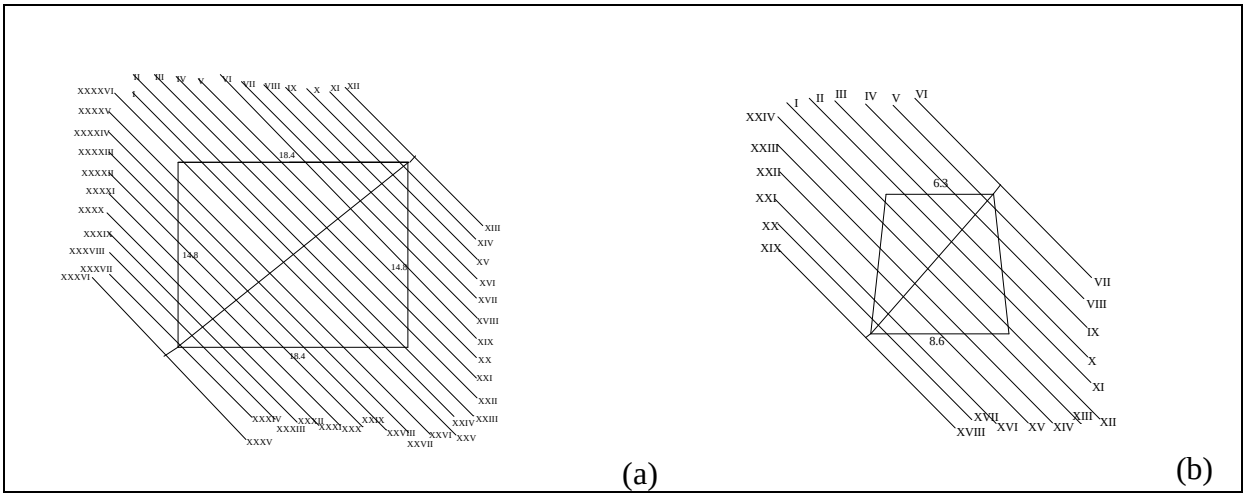

Figure 4: Plans that represent the exact place of the boreholes in relation to a) the building, which includes the tomb and b) the tomb.

Table 4. Length of boreholes for the corners.											
A/A	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
Length (m)	1.13	2.26	3.39	4.52	5.65	6.85	5.65	4.52	3.39	2.26	1.13

cm/sec, a silicate-based grout is proposed. The viscosity is 10 cp. At the depth from 9.6m to 13m, the permeability is 10^{-3} cm/sec. The most valuable grout mix is chrome-lignin and phenoplast. In this case the viscosity is 5cp.

The last estimation of the type of grout mix is shown on Table 1. The calculation of the radius of the grout is shown on Table 2. The indicative radius of grout pipe, which is used for this case is 2.5cm.

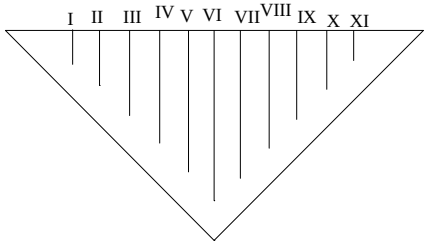

Figure 5: Indicative section by the place of the boreholes.

According to Raffle & Greenwood (1961), when the viscosity decreases, the radius of grout increases and vice-versa. So, if the quality of catalyst increases, there is a decrease in viscosity, in order the radius of grout to increase. Also, the radius of grout mix needs improvement at the specific depth, changing the concentration of catalyst on grouting techniques.

The actual number of groutings has calculated 24 for the tomb and 38 for the building that includes the tomb. Their exact place is shown on Figure 4 and the exact length of grouting pipes is shown on Table 3. The angle of the boreholes from walls and the depth direction will be 45^{o}.

If the groutings are located vertically around the tomb, the level of the watertable will fall to 32cm. So, the tomb will never become impervious as the capillary phenomens will rise the level of the watertable.

A simple grout mix can be used at soils which permeability is 10^{-2}cm/sec. The rate of the grout and water will be between 0.7 and 0.9 and the viscosity of grout mix will be 15cp (Raffle et al., 1961). The radius of the grout will be 60cm (Raffle et al, 1961). This solution can be used in order to reduce the total cost of the groutings.

As it is shown on Figure 4, only two corners of the tomb are covered by the grouting system. Two methods are proposed to solve this main problem.
The first method refers to the construction of two grout walls at the corners. The walls may be parallelepiped (dimensions of the tomb: A: 8x16m, B: 8.5x17m, dimensions for the building which includes the tomb: A: 9.07x18.14m, B: 9x18m) or triangular (Figure 5), (dimensions of the tomb: A: 16x8m, B: 17x8.5m, dimensions of the building including the tomb: A: 8.14x9.07m, B: 18x9m).

Table 5. Estimation of the type of grout for the Anthemion Tomb.

Borehole	Depth (m)	D_{10} (mm)	Permeability of soil (cm/sec)	Type of grout	Strength & Permeability data after grouting	Investigator
G3	3.20-4.10 5.0-7.00 7.00-7.5	0.015	$3.6 \cdot 10^{-3}$	AM-9	q_u=1242psi $ó_1$-$ó_3$=1230psi q_u=3.1kg/cm^2	Graf, 1982 Caron, 1963
>>	10.40-12.40	0.17	$2.25 \cdot 10^{-2}$	Silicate grouted sand Formamide or Formic Acid+Ethyl acetate	$ó_1$-$ó_3$=3200KN/m^2 q_u=250KN/m^2 (10 days curing)	Clough, 1979
>>	12.40-15.0	0.12	$1.7 \cdot 10^{-2}$	Silicate grouted sand Formamide or Formic Acid+Ethyl acetate	$ó_1$-$ó_3$=3200KN/m^2 q_u=250KN/m^2 (10 days curing)	Clough, 1979

Table 6. Calculation of the radius of grout for the Anthemion Tomb.

Borehole	Depth (m)	Injection head h (cm)	Porosity n (%)	Radius of injection pipe r (cm)	Time t (sec)	Ratio of grout viscosity to water viscosity a	Radius of grout R (cm)
G3	3.20-4.10 5.0-7.00 7.00-7.5	924 1520 1786	15	2.5	2100	10	41.18 48.61 51.3
>>	10.40-12.40	2348	10	2.5	2100	10	94.05
>>	12.40-15.0	2670	10	2.5	2100	10	89.41

Table 8. Calculation of the radius of grout for the Lysson & Kallikles Tomb.

Borehole	Depth (m)	Injection head h (cm)	Porosity n (%)	Radius of injection pipe r (cm)	Time t (cm)	Ratio of viscosity of grout to that of water a	Radius of grout R (cm)
G4	1.95-3.6	703	20	2.5	2100	10	43.03
>>	5.0-5.7	1241	20	2.5	2100	10	53.42
>>	6.8-7.5	1517	20	2.5	2100	10	58.66
>>	7.7-8.7	1663	20	2.5	2100	10	50.78

Secondly, some extra groutings are proposed in order the corners become impervious to water. The orientation of these boreholes is shown in Figure 5 and their lengths are shown on Table 4.

Impermeation grouting techniques in the protection of the Anthemion Tomb(3rd c. B.C.)

The Tomb consists of two rooms and presents Ionian style architecture. The principal facade and the inside walls are covered by frescos, the colors of which are in rather good condition The monument presents important weathering and static damages The front door of the monument is of white marble.

According to the borehole data, it was made an attempt on estimation of the type of the grout mix and calculation of the influence radius of the grout.

So, at the depth from 10.40 m to 15.0 m where D_{10} differs from 0.02 mm to 0.5 mm, the most valuable grout mixes are colloidal solutions or polymers such as silica or ligno chrome gels, tannins, organic colloids on polyurethane.

At the depth from 3.2 m to 7.50 m where D_{10} is less than 0.02 mm the most valuable grout mixes are pure chemical solutions such as acrylamides, aminoplast or phenoplast. The viscosity is 10 cp. The calculation data of the grout mix type and the grout radius are given in Tables 5 & 6.

Impermeation grouting techniques in the of the Lysson & Kallikles Tomb(200 B.C.)

This Tomb is considered as an exceptional architectural sample of that period.

At the depth from 1.95 m to 8.7 m where D_{10} depends from 0.02 mm to 0.5 mm the most valuable grout mixes are colloidal solutions or polymers such as silica or ligno chrome gels, tannins, organic colloids on polyurethane. At the depth from 11.50 m to 17.9 m where D_{10} is less than 0.02 mm the most valuable grout mixes are pure chemical solutions such as acrylamides, aminoplast or phenoplast. So, at the depth from 1.95 m to 8.7 m, where the permeability is higher than 10^{-2} cm/sec, a silicate-based grout is proposed. The viscosity is 10 cp.
The last estimation of the grout mix type and the grout radius are shown on Tables 7 & 8.

CONCLUSIONS

The conclusions of our investigation can be summarized as follows:

1. The studied Macedonian Tombs present important weathering and settlement problems.
2. The soil where these Tombs are buried is highly permeable, consisting mainly of gravel and clayey sand, alternated, in some cases, with thin layers of clay.

Table 7. Estimation of the type of grout for the Lysson & Kallikles Tomb.

Borehole	Depth (m)	D_{10} (mm)	Permeability of soil (cm/sec)	Type of grout	Strength & Permeability data after grouting	Investigator
G4	1.95-3.6	0.1	$1.44 \cdot 10^{-2}$	Silicate grouted sand Formamide or Formic Acid+Ethyl acetate	q_u=20kg/cm^2	Verfel, 1979
>>	5.0-5.7	0.13	$1.56 \cdot 10^{-2}$	Silicate grouted sand Formamide or Formic Acid+Ethyl acetate	q_u=34kg/cm^2 C=11kg/cm^2	Alam Singh et al, 1983
>>	6.8-7.5	0.14	$1.69 \cdot 10^{-2}$	Silicate grouted sand Aluminate+Amide	q_u=280psi	Karol, 1968
>>	7.7-8.7	0.1	10^{-2}	Silicate grouted sand Aluminate+Amide	q_u=280psi	Karol, 1968

3. The impermeation grouting techniques are suggested in order to protect the tombs from the water. The number of the boreholes that is needed to impermeate the building that includes the Krisis tomb is 46 and for the Krisis tomb is 24. The total length of boreholes for the first case is 750,54m and for the other one is 297,62m.

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