Crossing the Kifissos old river bed in the extension of the metro of Athens. Predicted and encountered water inflows

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Abstract: The main water-bearing medium, encountered by the tunnelling works for the Athens Metro extension to Egaleo city, is a conglomerate from the old deposits of Kifissos River. This conglomerate imposes significant head losses on the water movement, as ascertained by pumping tests. This fact was evaluated for the inflow prediction during tunnel construction. These values were estimated from few tens up to 300 m^3/h in the broader area of the tunnel face. The "active" inflows in front of the face were estimated much smaller. Given the good geotechnical behaviour of the conglomerate, these inflows did not justify the use of special measures and their control would be possible with drainage holes. During tunnel excavation, the observed inflows were found to meet the estimated values.

Résumé: L'aquifère principale rencontrée pendant la construction de l'extension du Métro d' Athènes vers l'Ouest, est constituée d' un conglomérat d' alluvions anciennes de la rivière Kifissos qui draine le bassin d' Athènes. Ce conglomérat provoque des pertes de charge importantes lors de l'écoulement souterrain constatées par les essaies de pompage. Cette condition a été prise en compte pour l'estimation des débits d'eau dans le tunnel du Métro en construction. Les flux prévus varient de quelques dizaines de m^3/h au front d'excavation lui-même, à 300 m^3/h dans sa proximité (jusqu' à 3 diamètres derrière le front). Ces débits, compte tenu également de la bonne qualité du conglomérat, ne justifieraient pas l'exécution des travaux spéciaux d'étanchéité. Le contrôle des débits pourrait être exécuté efficacement par des sondages drainants à l'avancement du tunnel. Finalement, pendant l'exécution des travaux, les débits constatés ont été trouvés cohérents aux débits prévus.

Keywords: tunnels, hydrogeological controls, transmissivity, pump tests, water table, case studies

INTRODUCTION

Line 3 of the Athens' Metro runs from the "Eleftherios Venizelos" airport at the East, to "Monastiraki" station at the West. The study area is part of its western extension to Egaleo city (Figure 1) and extends from "Aghios Savvas" station to "Votanikos" station (Figure 2). The interstation length is 1775 m. The double-track diameter (~10 m) tunnel is being excavated conventionally as an underground construction, in two phases, top heading and bench.

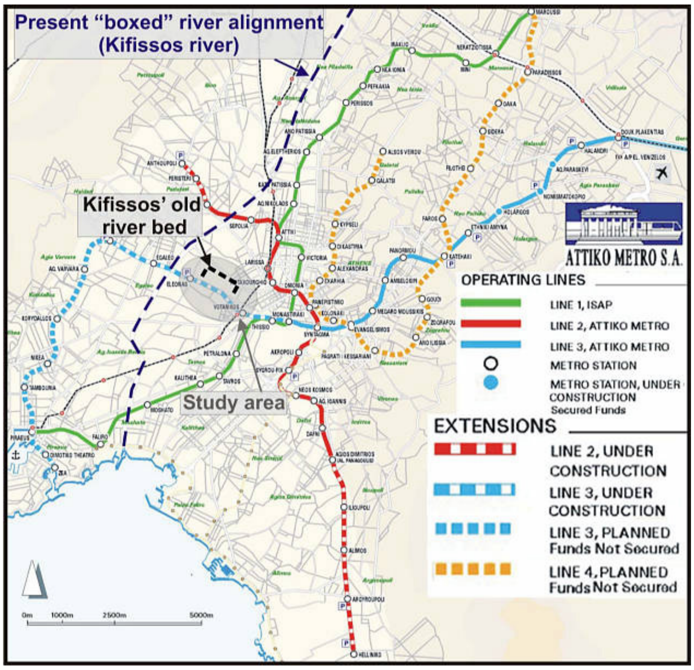

Figure 1. Athens’ Metro operating and extension Lines (http://www.ametro.gr).

A significant length of the extension (approximately from ch. 2+450 to 2+950) is situated in the old river bed of Kifissos river (Figure 2) which is the major drainage axis of the Athens’ basin. The present river bed is “boxed” and located to the west of the old one (Figure 1). In December 2002, construction started with excavation works at the “Prophet Daniel” intermediate access shaft. This shaft is located at chainage ~2+680, in the middle of the old river bed zone. Significant water ingress (~200 m^3/h) occurred during the excavation of the shaft, resulting in a temporary pause of the excavation works.

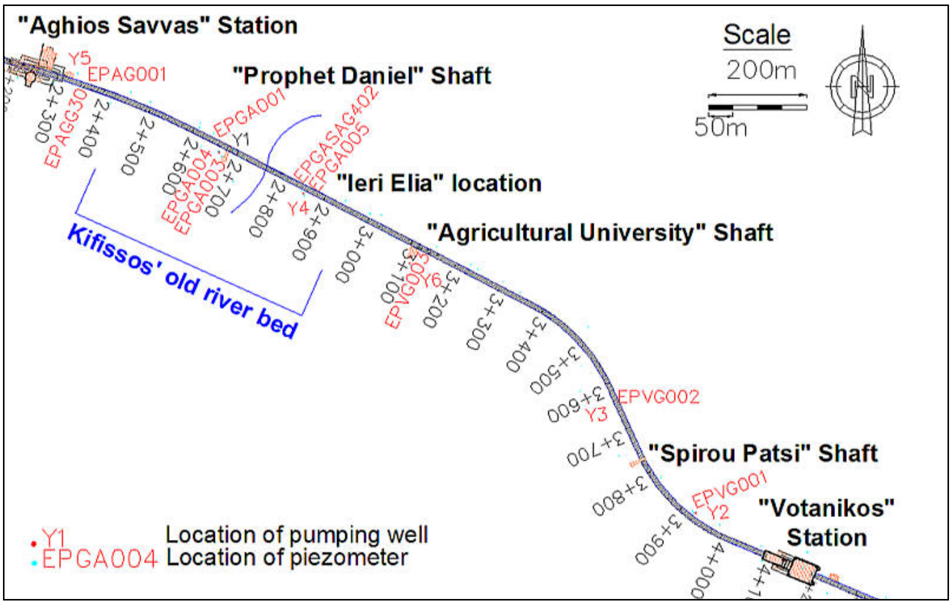

Figure 2. Plan view of the Metro alignment in the Kifissos river plain and location of pumping tests.

For the assessment of the hydraulic parameters of the water-bearing medium, in order to estimate the water inflows during construction, a pumping test programme was undertaken between April and June 2003 in the area between “Aghios Savvas” and “Votanikos” stations. In the mean time, tunnelling works continued utilizing only the “Spirou Patsi” (Figure 2) and “Knossou” (ch. ~1+770, not visible in Figure 2) intermediate access shafts, outside the area of the old river bed. In April 2004 the “Agricultural University” intermediate access shaft was constructed in the archaeological site of the University. Tunnelling works commenced from this shaft towards the NW and SE to meet the advancing faces from “Spirou Patsi” and “Knossou” shafts. As of December 2005 the top heading (phase A) has broken through and the bench (phase B) is due to be completed very shortly. Consequently, the ground water conditions and inflows are known.

GEOLOGICAL CONDITIONS

The geological bedrock of the area is the "Athenian Schist" (Marinos *et al.* 1971), a highly heterogeneous and slightly metamorphosed system that comprises a variety of lithological formations. In the project area, alternations of meta-sandstones with meta-siltstones were encountered.

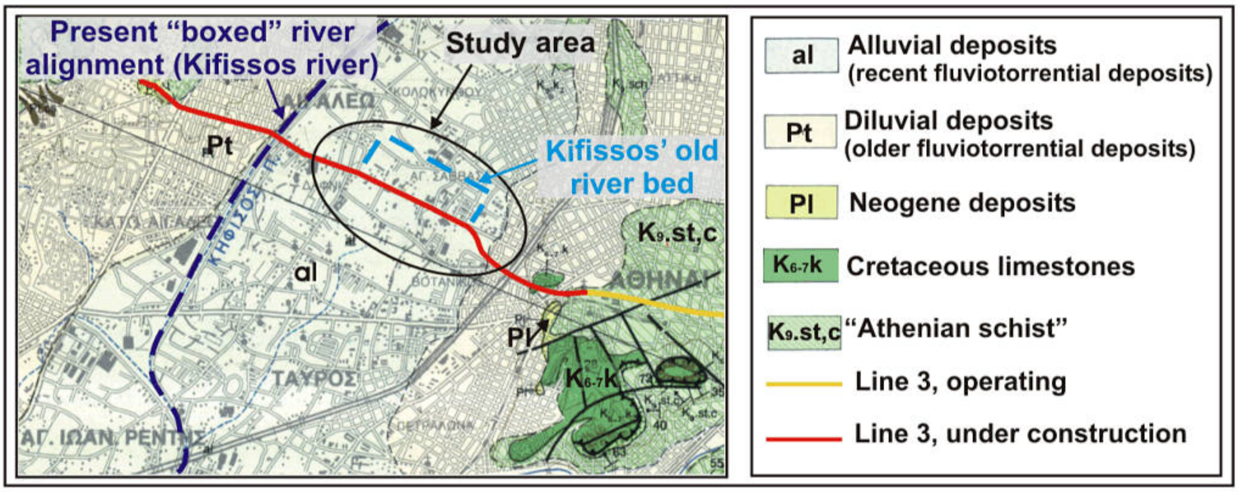

Figure 3. Geological map of the broad project area (I.G.M.E. 1982).

Over the "Athenian Schist", neogene sediments of clayey and sandy marls with intercalations of sandstones and conglomerates have been deposited. Quaternary fluviotorrential sediments cover these neogene strata or directly the "Athenian Schist" wherever the neogene deposits were eroded. It is possible to distinguish two different phases of deposition in the Quaternary sequence: a) the older, consisting of conglomerates and b) the recent, comprising alluvia of clay, silt and sand. The conglomerates are either coherent when the cement is of clayey-marly nature or well-cemented with a rock-like behaviour when calcareous cement is present (Figure 4).

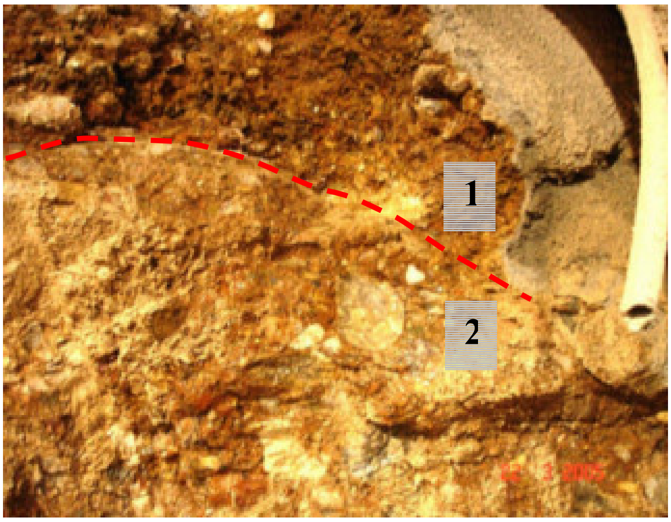

Figure 4. Coherent (1) or well-cemented (2) conglomerates at the tunnel face in the area of the old river bed (ch. ~2+885).

The nature of recent deposits is erratic in their spatial distribution with permanent variations in the participation of clay, silt, sand and gravel. Thus, the formation is highly heterogeneous with cross bedding and lateral transitions, forming zones of variable permeability. The total thickness of both older and recent deposits, according to the data from the site investigation, is approximately 40 meters in the area of the old river bed (area of "Prophet Daniel" access shaft, ch. ~2+680, Figure 5).

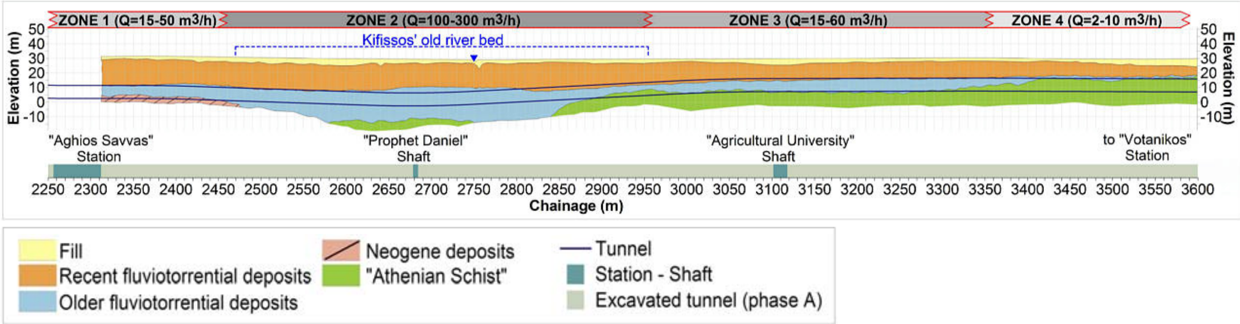

Figure 5. Schematic geological section of the extension of Line 3 of the Athens' Metro to Egaleo city, crossing the old bed of Kifissos river and zonation in terms of estimated water inflows.

Tunnelling works from "Spirou Patsi" shaft to chainage ~3+600 were undertaken in the formations of the "Athenian Schist". From chainage ~3+300 (Agricultural University area) up to chainage ~2+950 the tunnel was excavated in the conglomeratic environment of the old fluviotorrential deposits with the bedrock being at levels slightly lower than the red line of the tunnel. Recent fluviotorrential deposits were encountered at the upper part of the excavation profile only in few areas around the Agricultural University.

In the old river bed area (ch. 2+450-2+950) the thickness of the fluviotorrential deposits increases and the bedrock was identified in boreholes, well below the tunnel invert. The conglomerates in this area are well-cemented with a rock-like behaviour. In certain areas an impermeable, strong, clayey-marly formation was encountered on the top heading tunnel floor

HYDROGEOLOGICAL CONDITIONS

The "Athenian Schist" system is an impermeable formation. Low potential aquifers may only develop in the weathered mantle and the loose superficial zone of the formation.

The conglomerates of the old river bed are the main water-bearing media that were encountered by the tunnel excavation and they exhibited a non-uniform water flow pattern. More specifically, the permeability of the conglomerates, when they are just cohesive, fluctuates with respect to the nature and the composition of the cement material. When they are well-cemented, the degree of cementation between its components as well as the imperfections and flaws of the cementation, the existence of fractures (though they are limited due to the recent age of the formation) and the interconnection between them, which does not always seem to be continuous, appear to control the underground flow.

The recent deposits, generally of fair permeability, host an aquifer that may be of sufficient potential when their thickness is significant. It is possible that they may form a continuous aquifer medium with the underlying conglomerates yet, obviously, water flow in each formation differs with respect to its permeability.

Figure 6 shows the contour map for high ground water level at the Kifissos river hydrogeological basin, with its main drainage axis coinciding with the old river bed, being perpendicular to the axis of the tunnel. The average hydraulic gradient along the drainage axis is approximately 10 ‰ (Kounis 1981) due to the flat topography of the plain.

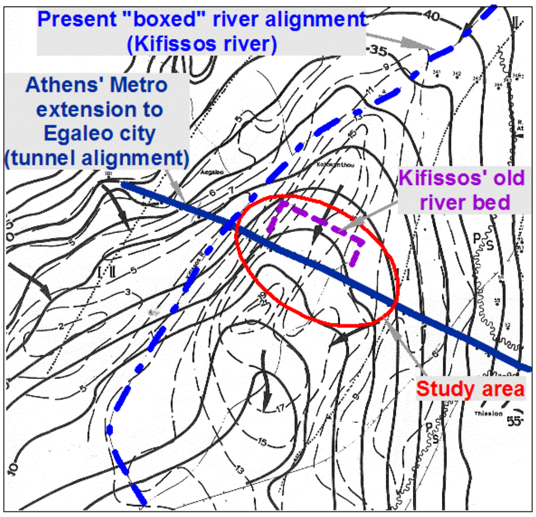

Figure 6. Contour map for a high groundwater level period (Kounis 1981).

THE BEHAVIOUR OF THE WATER BEARING MEDIUM AND THE SELECTION OF APPROPRIATE HYDRAULIC PARAMETERS FOR THE ESTIMATION OF WATER INFLOWS IN THE TUNNEL

During the site investigation programme in situ permeability tests, mostly falling head, were executed. These tests indicated that along the tunnel alignment generally low values of permeability ($k<10^{-6}$ m/s) were measured. This is probably due to the fact that the tested parts in boreholes often coincide with fine grained zones in the alluvia. Higher permeability values (up to 10^{-4} m/s) were recorded at the central part of the alignment (ch. 2+900 – 3+000), as can be seen in Figure 7. The pumping tests in wells and pumping boreholes, performed afterwards, allowed a further estimation of more representative hydraulic parameters of the surrounding ground in order to calculate the water inflow during tunnel construction. The programme involved the drilling of wells and piezometers in six selected locations (Y1 to Y6 in Figure 2 and Figure 7). The permeability values that derived from the pumping tests were, as expected, higher than the corresponding in situ falling head test values. Pumping tests must always be considered as more reliable than falling (or constant) head tests which are of a punctual manner. Groundwater level measurements, taken during the pumping tests were analysed using the Theis method and the Cooper- Jacob approach for both drawdown and recovery.

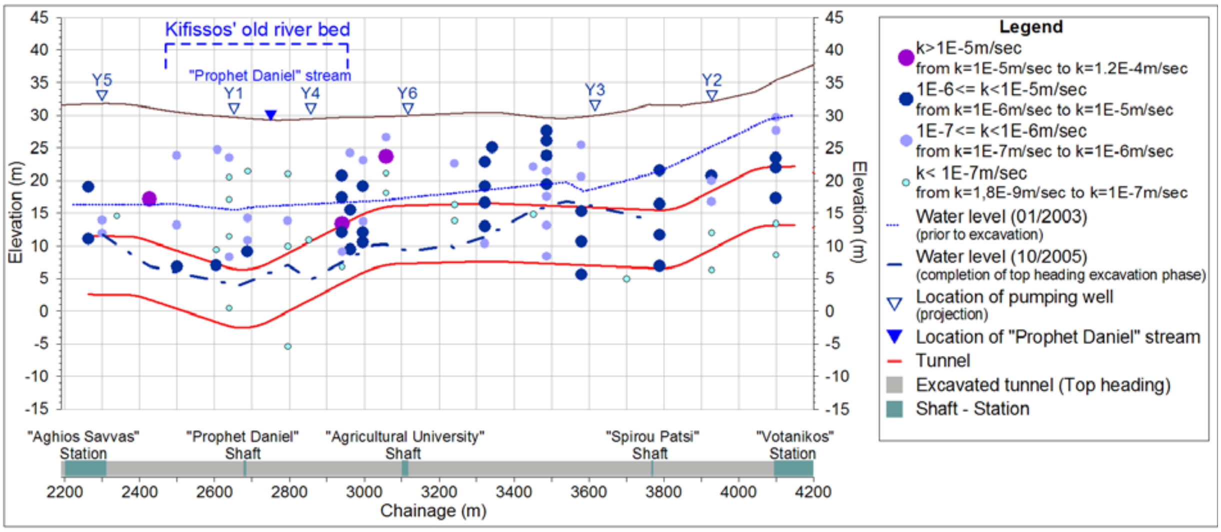

Figure 7. Permeability distribution graph along the alignment based on in situ punctual permeability tests.

The analysis of the measurements of the ground water level recovery in the pumping wells provided two values of transmissivity T (Figure 8), contrary to the analysis in the satellite piezometers which provided a single value (Figure 9). It was considered that the lower value of transmissivity is affected by the head losses due to the difficulty of circulation of the ground water in the inhomogeneous and discontinuous aquifer medium of the conglomerates during its radial flow to the pumping well. These head losses obviously do not occur in such extent in the piezometers.

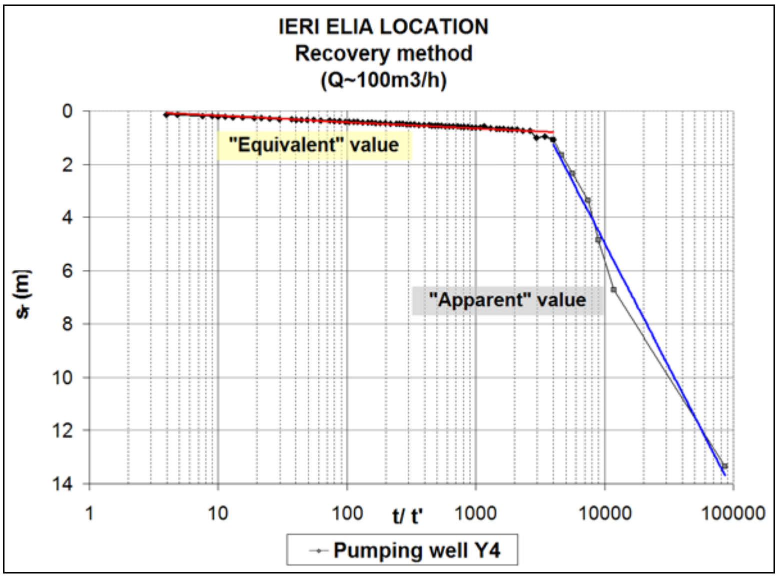

Figure 8. Recovery of the pumping well Y4 at Ieri Elia location in the old river bed.

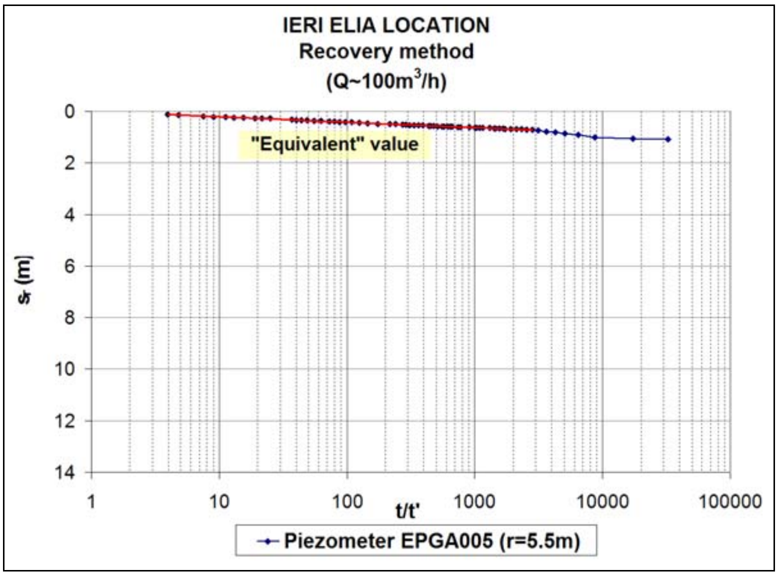

Figure 9. Recovery of a piezometer 5.5 m adjacent to the pumping well Y4 at Ieri Elia location.

Note in Figures 8 and 9: Q is average pumping rate (m^3/h); s_r is residual drawdown (m), t . time elapsed after start of test (pumping + water level recovery), (s); t' time elapsed after stop of pumping (water level recovery), (s), and r distance of piezometer from the pumping well, (m)

The higher value of transmissivity is the one which reflects, as a whole, to the potential of the unified water-bearing system which is formed by both the recent and the older fluviotorrential deposits. This value was appointed the term "equivalent". The lower value, we considered that is controlled by the particularities of the flow paths in the conglomerates and was appointed the term "apparent". The "apparent" and "equivalent" values of transmissivity are given in Table 1. This dual behaviour can be tracked down across the whole area of the tunnel passing through the Kifissos' bed, though differentiated in terms of magnitude. As expected, the maximum values of hydraulic conductivity were found at the area of "Prophet Daniel" shaft and at Ieri Elia area (10^{-3} m/s), where the old river bed is located, with a gradual attenuation towards the basin edges. Accordingly, at the lateral zones, at "Aghios Savvas" station and the area of the Agricultural University, permeability values in the range of 10^{-4} m/s were recorded, while at "Spirou Patsi" shaft area the corresponding range is that of 10^{-6} to 10^{-7} m/s.

Table 1. "Equivalent" T_{eq} and "apparent" T_{app} values of transmissivity T and permeability k.

Location	Well	Chainage	T (m^2/s)		k* (m/s)	
			$T_{app.}$	$T_{eq.}$	$k_{app.}$	$k_{eq.}$
"Aghios Savvas" Station	5	2+300	$4.0x10^{-4}$	$3.0x10^{-3}$	$4.0x10^{-5}$	$3.0x10^{-4}$
"Prophet Daniel" Shaft	1	2+652	$8.0x10^{-4}$	$1.5x10^{-2}$	$4.0x10^{-5}$	$8.0x10^{-4}$
Ieri Elia Area	4	2+857	$3.0x10^{-3}$	$3.0x10^{-2}$	$3.0x10^{-4}$	$3.0x10^{-3}$
Archaeological site at the Agricultural University ("Geoponiki" Shaft)	6	3+116	$3.0x10^{-4}$	$6.0x10^{-3}$	$3.0x10^{-5}$	$6.0x10^{-4}$
Agricultural University	3	3+617	$3.0x10^{-6}$	$4.0x10^{-5}$	$3.0x10^{-7}$	$4.0x10^{-6}$
"Spirou Patsi" Shaft	2	3+929	$5.0x10^{-6}$	$1.0x10^{-5}$	$2.5x10^{-7}$	$5.0x10^{-7}$

* The respective aquifer thickness was used for the estimation of the hydraulic permeability coefficient, k.

The question that arises is which value should be applied for the calculation of the water inflow in the tunnel during construction. As an initial consideration the "apparent" value could be used since the tunnel would be mainly excavated in the conglomerates environment. In all probability such an option might have been too brash and not provide the necessary safety in the inflow calculations given that the water-bearing medium is heterogeneous. Moreover, there may be strong variations present from place to place. As such, a value at a maximum of 70% of the "equivalent" value was selected: a value which the authors considered to be still conservative. This value was assigned the term "corrected".

WATER INFLOW ESTIMATION DURING TUNNEL CONSTRUCTION

The area was divided into 4 zones of similar hydrogeological behaviour with respect to the prevailing values of permeability and the extent of the geological formations (Figure 5). Water inflow in the area of the tunnel face is a three-dimensional problem, time dependant and controlled by the tunnel advance rate. Consequently, the calculations that follow are inevitably approximate. However, this approach allows for estimations that do not exceed the scale of demands of a tunnel construction.

The average inflow q in the tunnel face per linear meter of excavation can be estimated by a modified Theis equation (Kavvadas 2004) for two dimensional conditions on a plane perpendicular to the tunnel axis:

$$q = kB\left(\frac{s_W}{R}\right)(2H - s_W)$$

$$R = 1.5\sqrt{\frac{Tt}{S}}$$

where q is the water inflow in the tunnel face in m^3/s per linear metre, s_w is the total drawdown of the aquifer due to the tunnel excavation in m, H the thickness of the aquifer in m, R the radius of influence in m, T the transmissivity of the aquifer in m^2/s, k the permeability of the aquifer in m/s, S the storage coefficient of the aquifer, B the width of excavation in m and t the time in s.

Assuming that the inflows at the tunnel face are controlled by a broad zone along the tunnel axis, equal to about 3 tunnel diameters (L), namely from in front of the tunnel face up to 15-20 m behind the face, in a time interval of 14 days (an estimated period associated with the advance of the tunnel), the anticipated water inflows are presented in Table 2.

However, these estimated inflows are not the effective discharge that may endanger the stability of the advancing face. Thus, as “effective” discharge is considered here to be the one which converges at the unsupported length during the excavation process, namely, slightly more than the advance step by1-3 m.

Table 2. Estimated water inflows during construction at the greater tunnel face area.

Zone	Chainage (from-to)	Area	Geological-Hydrogeological conditions	Estimated water inflow in a broad area, approximately up to 15-20 m behind the tunnel face (m^3/h)
1	2+200-2+450	“Aghios Savvas” Station	Fluviotorrential deposits limited in thickness by the rise of the bedrock.	15-50
2	2+450-2+950	“Prophet Daniel” Shaft / Ieri Elia Area	Kifissos’ old river bed. Significant thickness of fluviotorrential deposits.	100-300
3	2+950-3+350	Archaeological site of Agricultural University (“Geoponiki” Shaft)	Fluviotorrential deposits limited in thickness by the rise of the bedrock.	15-60
4	3+350-3+770	Agricultural University	Limited presence of fluviotorrential deposits due to further rise of the bedrock.	2-10

HANDLING OF WATER INFLOWS

The first impression induced by the high water inflow in the “Prophet Daniel” shaft during its excavation (~200 m^3/h), which intersects the whole water-bearing system, and the generally significant values of permeability that initially derived from the pumping tests, led to the consideration that a grouting programme for the reduction and control of the water inflows would be necessary. With reference to this, a pilot grouting programme was executed by the Contractor in an area of 240m^2 around the “Prophet Daniel” shaft (Koronakis *et al.* 2005).

However, the authors assumed that the differentiation in the hydraulic behaviour was due to the head losses during the flow of water towards the tunnel through and within the conglomerates, and that this should reduce the inflows to acceptable levels for the construction of the tunnel without the need to apply special treatment measures. These levels are acceptable for both water inflow handling and for tunnel stability. Indeed, in terms of safety, the conglomerate is in all cases of good quality; either well-cemented of high strength and not prone to erosion, or just cohesive with a marly-clayey cement which renders the conglomerates a low permeability formation.

These conditions form a good, in geotechnical terms, environment for the excavation of the tunnel and water control can be achieved by drainage holes, which can also easily reduce the hydraulic head in front of the tunnel face.

COMPARISON BETWEEN ENCOUNTERED AND ESTIMATED WATER INFLOWS

During tunnel construction and until its completion, the encountered water inflows were always inside the frame of the estimations thus validating the assumptions discussed in the previous paragraphs. Furthermore, having in view that the coincidence between estimated and encountered values is, more or less, in the middle of the range of the estimations, it would be possible to use even a lower "corrected" value of transmissivity, even lower than 50% of the "equivalent" and closer to the "apparent" value.

Both the estimated and encountered inflows in a broader area of the tunnel face (at the face and up to 15-20m behind it) are shown in Table 3, together with the "effective" discharges encountered at the tunnel face itself.

Table 3. Estimated and actual water inflows during the construction of the tunnel

Zone	Tunnel section in the hydrogeological zone (ch.)	Water inflows at the tunnel face and up to 15-20m behind it (m^3/h)		Maximum observed inflow values at the tunnel face it self (m^3/h)
		Estimated (Table 2)	Maximum measured	
1	"Aghios Savvas" area (2+200-2+350)	15-50	40	15
2	"Prophet Daniel" Shaft / Ieri Elia area (2+680-2+950)	100-300	140	45
3	Archaeological site of Agricultural University ("Geoponiki" Shaft) (2+950-3+450)	15-60	50	15
4	Agricultural University (3+450-3+600)	2-10	10	3

Discharge measurements were taken at the intermediate access shafts, where water was collected from both advancing faces. These discharges correspond to the cumulative inflow which was drained by the tunnel across its whole length and they do not correspond in any case with the section that was being excavated (Table 4). It is clear from this table the result of the drainage provoked by the advancing tunnel. Indeed, the cumulative discharges are just higher than those of the face broader area. This observation demonstrates the effectiveness of drainage holes that were drilled at the same time with the tunnel advance (face and tunnel sides).This issue is also discussed in the next paragraph.

Table 4. Cumulative water inflows measured at the corresponding intermediate shafts during tunnel construction.

Zone	Tunnel section in the hydrogeological zone (ch.)	Excavated tunnel length (m)	Cumulative measured discharges of the overall excavated tunnel length (m^3/h)
1	"Aghios Savvas" area (2+200-2+350)	150	60-80
2	"Prophet Daniel" Shaft / Ieri Elia area (2+680-2+950)	270	200-350
3	Archaeological site at the Agricultural University ("Geoponiki" Shaft) (2+950-3+450)	500	40-100
4	Agricultural University (3+450-3+600)	150	10-20

RESPONSE OF MONITORING PIEZOMETERS AND ADDITIONAL OBSERVATIONS

In the area of the Kifissos' river bed (Zone 2), the conglomerate of the older phase of deposition is well-cemented and exhibited a rock-like behaviour. However, as already discussed, due to an occasional or incomplete cementation, porosity is not continuous and as a result the inflows at the face are non-uniform, localized, selective (Figure 10) and, occasionally high.

Figure 10. Water flow through the conglomerates of the old river bed at the tunnel face.

In the area of the old river bed ("Prophet Daniel" shaft / Ieri Elia area), the inflows in the restricted area of the tunnel face were reaching, as observed, 45 m^3/h (Figure 11). As excavation further proceeded, the inflows in the face area itself dropped at levels lower than 10 m^3/h.

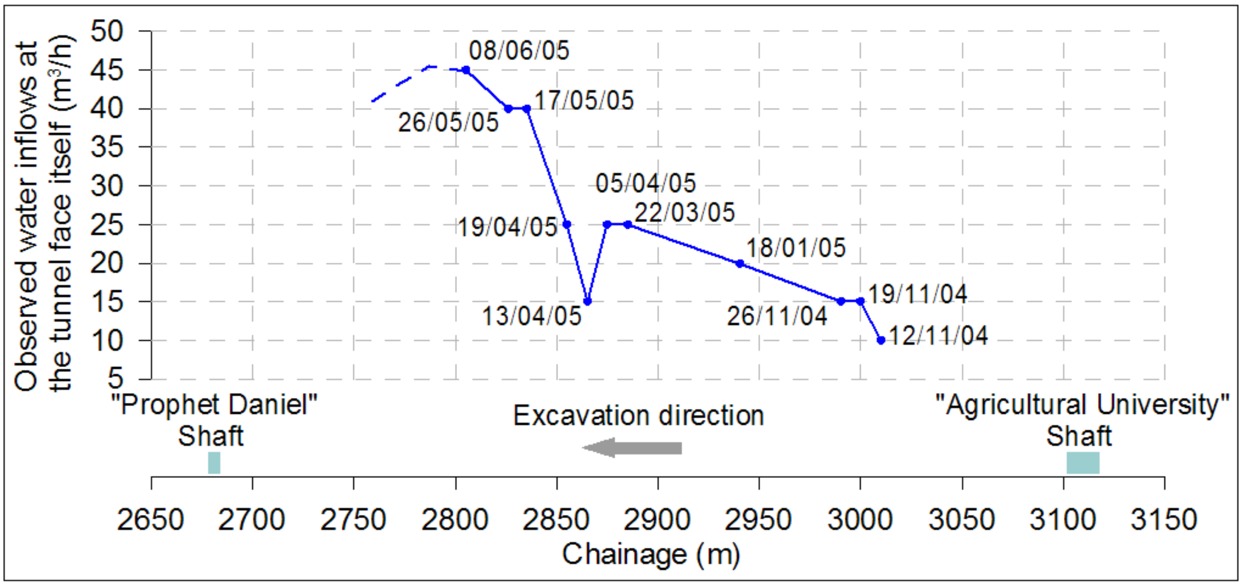

Figure 11. Water inflow course in the tunnel face as approaching the old river bed. The river bed starts at ch. ~2+950.

Drainage holes at the face as well as at the tunnel sides performed efficiently and the majority of water quantities were discharged in through the tunnel using these holes (see Figure 12). To some degree this is due to the discontinuous development of water flow paths. The water that flowed in the tunnel was clear; a fact that assured the absence of erosion and piping phenomena.

Drainage was utterly effective, not only for the control of inflows but also for the drawdown of the hydraulic head in front of the face and above the tunnel. The drained water table level was even reaching the level of the top heading floor.

Figure 12. Water inflow from the tunnel side through drainage holes at the area of the old river bed.

From the response of the piezometers it appears that the water table level, around the tunnel in the conglomerate environment, dropped relatively fast. This was fact due to the delay in the replenishment of the drained ground water and as such a reduction is produced in the high loads around the tunnel. Water table measurement analysis in piezometers showed that this drawdown was stretching well ahead of the excavation face. Specifically, as shown in Figure 13, the water table level in piezometers starts to respond when the advancing face approaches them at a distance of more than 100m. The drawdown reaches 2-4m when the advancing face intersects the piezometer projection on the alignment. Drawdown obviously continues after this intersection at a rate, which depends on the potential of the aquifer. The rate of drawdown with time in the piezometers is indicated in Figure 14.

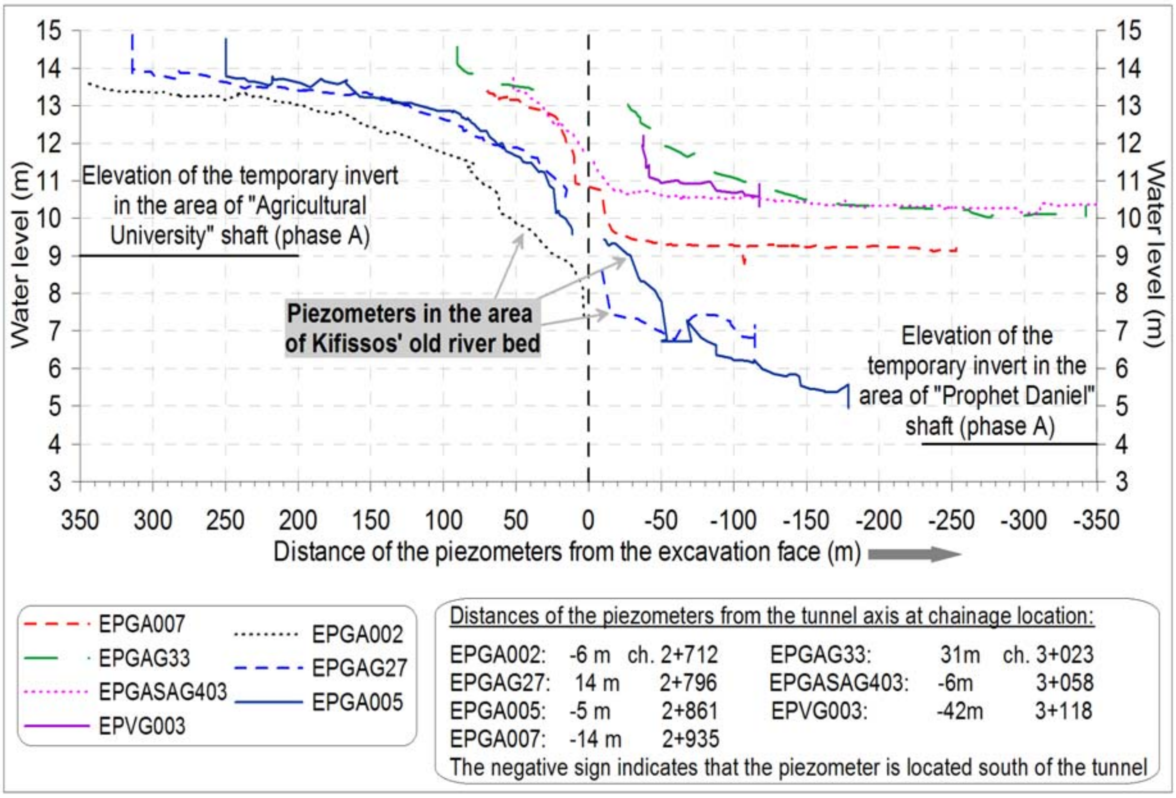

Figure 13. Water table drawdown against piezometer distance from the excavation face.

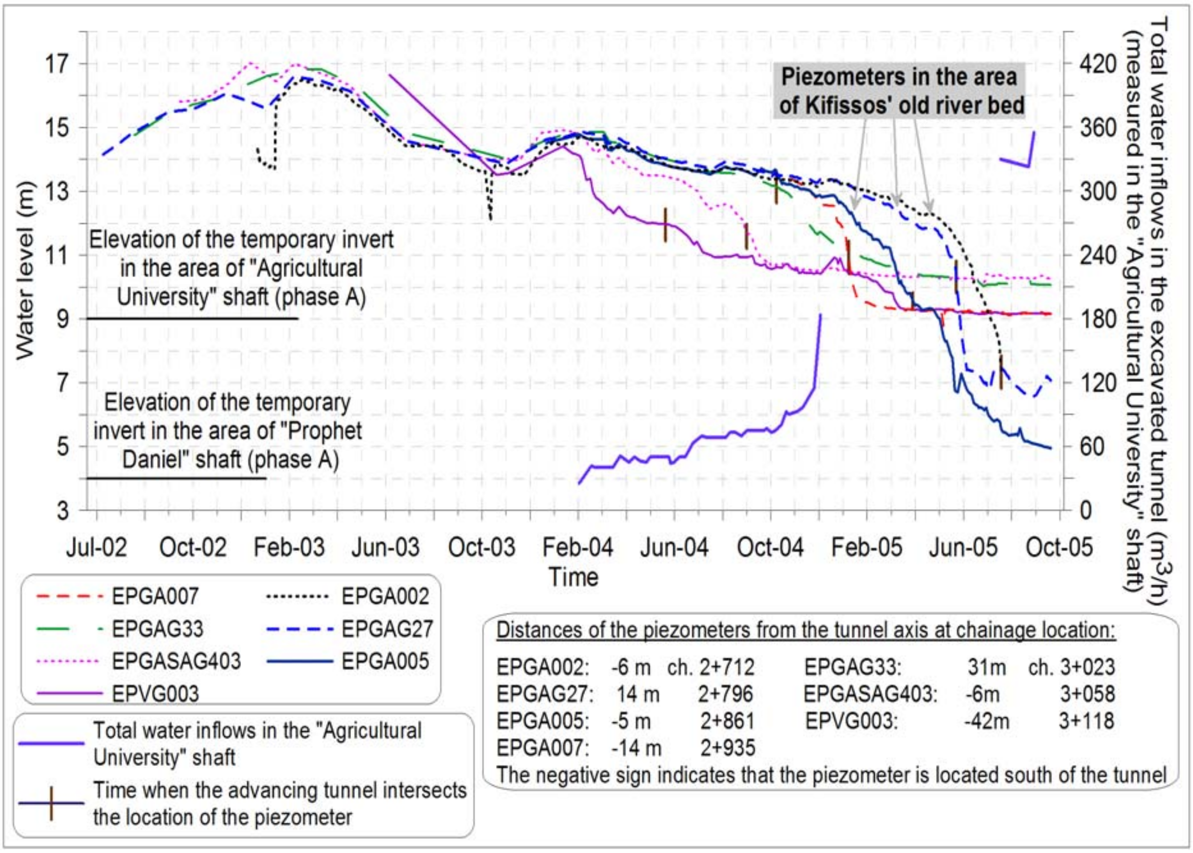

Figure 14. Water table drawdown and water inflows measured at the shaft in the area of the Agricultural University (ch. 3+100).

CONCLUSIONS

The evaluation of the geological data of the Kifissos' old river bed formations and the selection of the appropriate transmissivity values that take into account the head losses due to the particularities of the radial water flow in a discontinuous conglomeratic medium, allowed the proper prediction of the inflows in the tunnel for the western extension of Athens' Metro. This prediction imposed from the beginning meant there was confidence that the tunnel could pass the old river bed without any treatment. Indeed, during construction, the inflows were managed with ordinary measures such as drainage holes.

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