Subsidence phenomena in Anthoupoli district of Peristeri municipality in western Athens, Greece

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Abstract: The intense and rapid urbanization of Anthoupoli district, part of Peristeri suburb of Athens, after the Second World War brought an end to coal mining activity started in 1930 and operated with underground workings. The lack of permanent protective measures to the whole galleries network, which was and still is practically unknown, caused, after some years, the manifestation of instability phenomena. The latter are continued even today, 40 years later, generating problems on the existing structures and making them very sensitive to dynamic loading. Thus, damages caused by the earthquakes of 1981 and 1999 were more serious in Anthoupoli than in any other part of Peristeri municipality.

For better protection of the district, an engineering geological study was carried out to examine the geotechnical problems in the urban area above the mines. This investigation included drilling works, in-situ and laboratory testing, engineering geological mapping and some geophysical (seismic refraction) surveys. The evaluation of collected data confirmed that the deterioration of the (unrecorded lignite) galleries that were abandoned without protection measures led to collapse of certain parts of them. Furthermore, the migration of the cavity process resulted in the manifestation of subsidence phenomena at Anthoupoli district. As the whole process depends on many parameters, subsidence phenomena occur suddenly and at different times in various parts of the district, causing serious problems to houses such as cracks on the walls, tilting of whole buildings, separation of construction elements, disturbance of foundations etc.

Thus, relying upon the compiled engineering geological map and using all the information gained, a risk map of the area was compiled and instructions were formulated for safe construction in the sensitive zone.

Résumé: L'urbanisation à Anthoupolis, un quartier de la ville "Peristeri" qui se trouve 5Km à l'ouest d'Athènes, était si intensive et rapide, après la 2ème guerre mondiale, qui a résulté à l'arrêt d'exploitation souterraine de la mine lignitifère qui était active depuis 1930 dans cette région. L'absence de mesures de protection à tout le réseau de galeries d'exploitation, à provoqué de conditions d'instabilité quelques années plus tard ; Elles continuent jusqu'à nos jours quarante ans après, et causent de problèmes sérieux aux constructions de ce quartier, comme elles se deviennent prenables aux tremblements de terre. C'est pourquoi les constructions provoquées par les séismes du 1981 et 1999, et sont enregistrées au quartier d ' Anthoupolis, étaient beaucoup plus graves qu'à celles, aux autres quartiers de la ville "Peristeri".

Afin d'assurer la meilleure protection de la région urbaine, on a élaboré un projet géotechnique pour examiner les problèmes d'instabilité. Ce projet contenait un programme de forages accompagnés par des tests "in situ " et au laboratoire, le levé de la carte technico-géologique de la région, ainsi que des recherches géophysiques. L'évaluation des résultats obtenus nous a amené à vérifier que l'affaissement d'un part des galeries abandonnées est due à la détérioration de ces galeries sans mesures de protection. En plus la migration du cavité vers la surface, dérivée par cet affaissement résulte à la manifestation de phénomènes subsudants au territoire urbain d' Anthoupolis. Comme tout ce processus dépend de plusieurs paramètres, les phénomènes de subsidence du sol peuvent être inattendus à n'importe moment et endroit du territoire urbain provocant des problèmes sérieux, comme destruction aux fondations et fissures aux murs des édifices ou même inclinaison du bâtiment entier.

En plus on a composé une carte de risque géologique, conformant toutes les instructions à construire et fonder en sécurité dans la zone sensible.

Keywords: coalmines, lignite beds, back fills, subsidence, engineering geology map, subsidence risk assessment.

INTRODUCTION

In Anthoupoli district an area of about 6 km^2, which belongs to the municipality of Peristeri, one of the western suburbs of Athens (Figure 1) and the fourth, in population order, municipality in Greece, coal (lignite) mines in Neogene deposits (Peristeri-Kalogreza basin) operated during the period 1930 to 1959. Before 1950 efforts of the State were focused towards investigation works and optimization of the excavation techniques, while soon afterwards, exploitation activities were intensified. Consequently, serious problems arose in the strongly urbanized area, above the lignite mines, due to noise, vibrations and continuous degradation of the city environment and private properties. It must be noted, that the increase of the inhabitants in the area of Peristeri after the World War II was so rapid, that the population of the municipality rose from 40.000 in the 50's to 140.000 in the 80's.

Under these circumstances, the State, in order to face the complicated situation, decided to stop immediately the operation of the mines and focused attention to remedial works. These works intended to maintain the roof of the existing adits and avoid extended collapse, which could affect the above-founded urban area. Although some measures were taken, such a phenomenon was likely to occur, after a time period, depending on many parameters, hard to be estimated in advance. In fact, sparse damages on the buildings were observed, indicating instability phenomena. Gradually more structures appeared to be affected, while the area influenced by these phenomena increased rapidly. The detection of the underground processes, which were manifested in the urban environment as building failure and the evaluation of the degree of danger they represent, constitute a major issue for civil protection. These phenomena continue even now, causing instability problems in the existing structures and making them very sensitive to dynamic loading, as it is revealed from the damages caused by the earthquakes of, 1981 and 1999. In 1995, the local authorities decided that a full investigation of the problem should be carried out, in order to investigate the ground conditions, assess the origin and mechanism of the problems observed and enable sustainable planning for the urban area of Anthoupoli (Rozos et al, 1999).

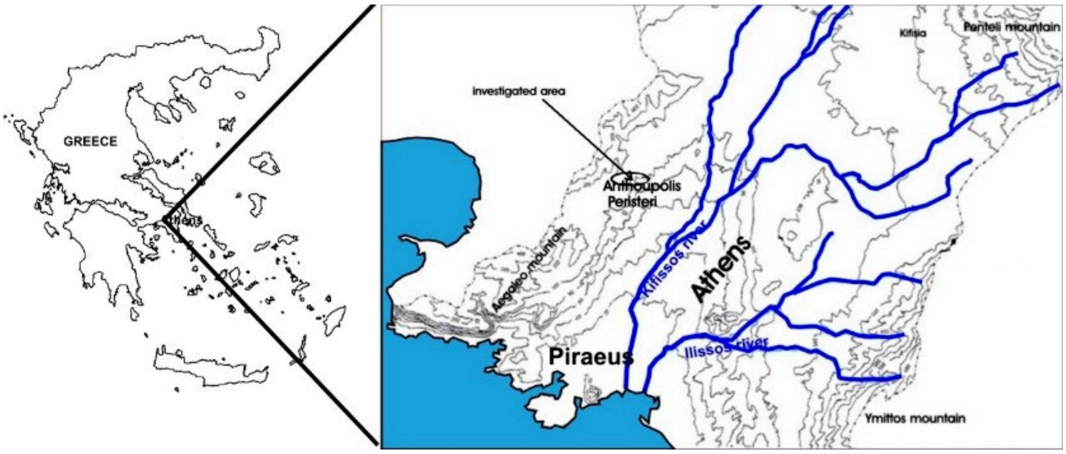


Figure 1. Location map of the examined area.

GEOLOGICAL SETTING AND HYDROGEOLOGICAL CONDITIONS OF THE STUDIED AREA

The wider area of Peristeri municipality belongs to the basin of Kalogreza – Peristeri, consisting of Neogene sediments with lignite beds. The area under study is characterized by a low relief, starting from an elevation less than 60m above sea level and rising up to about 200m at the hills located at the northwestern edge of the study area. The morphological inclination dipping to the southeast becomes very smooth from the western border to the east.

Regarding the geological structure of the broader area of Attiki (Athens), according to Katsikatsos et al. (1986), the surrounding mountains of Aegaleo and Parnitha consist of non–metamorphic Alpine formations of the Pelagonian zone, overthrusting the autochthonous units of Attiki (mount Penteli), which belong to the Tripoli-Gavrovo zone and outcrop as tectonic windows. Between the Aegaleo and Parnitha mountains on the west and Penteli on the east, an extended Neogene - Quaternary basin is formed. These sediments cover the thrust line and bear the major urban activity of Athens city and its suburbs. In accordance with the aforementioned, Anthoupoli area is formed of Neogene sediments, overlying the Aegaleo Mesozoic rocks (Athenian schists and limestones). These rocks constitute the geological basement of the Neogene sediments and are exposed at the southeast as well as to the southwest borders of the study area.

Regarding the hydrogeological conditions, the wider area of Peristeri Municipality belongs to the basin of west Kifissos River and the geological formations that play a significant role to the hydrogeological regime of it are the Neogene sediments and the Quaternary deposits. The former as a whole are characterized as impermeable formations due to the presence of thick impermeable layers, which confine lens-like horizons of various coefficient of permeability. Measurements in boreholes and wells showed that the water table of these confined aquifers in Neogene sediments ranges between 3 and 12m, according to geomorphology, lithology and stratigraphy of every site. Also they present a fluctuation of its level, up to 1m annually. Therefore, confined aquifers of rather low capacity can be locally found, from which water was pumped out in the past for irrigation purposes, but today this happens to a limited extend.

In more details the geological structure, the lithological composition and the hydrogeological regime of the formations, which appear in the wider Anthoupoli area from the new to the old, are as follows:

- Recent fills, which have thickness as ranging from several meters in the site of central mining works to 1 or 2 meters elsewhere. In the site of the main mining activity, they consist of remoulded and locally compacted material from various lithological types of the Neogene deposits and have a random composition, like fines of marly constitution and limestone grits and gravels (up to 8 cm). In other areas they are silty sands with grits and gravels (up to 6 cm).
- Alluvial deposits that are grey clayey silts or silty sands to sandy silts with grits and gravels of various size and composition, mainly up to 4 cm, consisting of limestone. The coarse grained phases (sands and gravels) predominate at the central area of Anthoupoli, where the alluvial deposits reach 3 to 5 m in thickness, while in

the rest area they usually appear up to 3 m. This formation is loose to semi coherent, generally permeable and covers either the Neogene sediments or the alpine basement.

- Fan deposits, which are Pleistocene in age and located at the northern, western and southwestern edge of Anthoupoli district, especially at the foot of the hills where they are usually formed. They are reddish-brown cohesive fanglomerates. The fine-grained fraction consists of clayey silts to silty sands of brown reddish colour whereas the coarse elements (rock fragments) are of limestone, schist or quartz origin with a size up to 10-15 cm. This formation shows a thickness between 1 and 6 meters and is of medium permeability; so, aquifers of limited extent are formed at places, where they are in contact with impermeable Neogene horizons or the schist basement.
- Neogene sediments that consist of various horizons, alternating horizontally and in places vertically as well. Nevertheless according to site investigation and relevant references, these strata can be divided into the following three units: a) calcitic marls alternating with marly limestones, predominate at the morphologically higher places of the western part of Anthoupoli, b) marls to clayey marls interbedded with coarse grained phases as sands, sandstones and gritstones, prevail in the central and eastern part of the study area and c) grey cohesive marls to siltstones, which compose the deeper horizons and mainly include the lignite seams. The marls, clayey marls and siltstones are impermeable, while sands, sandstones, gritstones, conglomerates and marly limestones differ in permeability, in accordance to their grain size and fracturing. The lignite seams do not constitute a uniform horizon but a sequence of lignite intercalations, the quality of which differs from place to place from compact lignite to plastic clayey lignite layers. Thickness of these lignite beds varies from a few tenths of centimetres up to more than 17 meters. Lignite appears at the depth of 30m and exceeds the depth of 250m, but main exploitation activity in Peristeri, took place between 30m and 90m from the surface. The total thickness of the Neogene sediments exceeds 300m.
- Athenian schists, which are flysch like formations and constitute the Alpine basement of the area under study, green - grey in colour, strongly folded and fractured, with intense schistosity. Locally, lenses (up to a few meters) of crystalline grey limestone, as well as quartz intercalations, of few centimetres in thickness are met. These formations can be considered impermeable, due to their composition and structure. Only within the limestone intercalations of the Athenian schist, confined aquifers are met. They are prone to weathering near the surface because of their lithology and physical condition, and are covered by a weathering mantle of varying thickness.
- Aegaleo limestones that are grey in colour, and Cretaceous in age, intensely fractured, with high proportion of calcitic-marly material. Therefore, they show a high secondary permeability, which helps bringing in water laterally to the Quaternary formations and to Neogene deposits. In places they are covered by scree, with a thickness up to 1m.

The surface development of the above formations can be seen in the engineering geology map of Figure 2.

TECTONICS

Three fault systems can be recognized in the broader Athens area. The older one is a major NE-SW striking fault system, starting from Central Euboea and ending in Peloponnesus, through Attica (Athens basin). The NE-SW striking fault system probably originated as a Tertiary thrust and later, during Middle to Late Miocene time, experienced a vertical reactivation. Since early Pliocene time, it has been reactivated with slight anticlockwise rotation towards a NNE-SSW strike, while major vertical displacements occurred along this system (Dietrich, *et.al.*, 1991). Vertical displacements also acted since the Pliocene, along the second major fault system that has an E-W direction, while the third fault system, which appears to be the youngest identified in the area, strikes NW-SE.

Apart from faulting, folding also has affected the Alpine formations as it is revealed by the multifolded structure of the Athenian schist (Andronopoulos & Koukis, 1976). Intense folding and faulting together with the anisotropic behaviour of the schist basement created the morphological features, in which the formation of the Neogene basin dominates.

The above-mentioned tectonic factors were also reactivated after the deposition of Neogene sediments, affecting them and the Pleistocene formations as well. Further on, intense erosion created today's low relief, while due to urbanization the aforementioned tectonic lines can hardly be recognized in the area of Anthoupoli. Thus, only at the northwestern part of it, two major fault lines can be assumed without showing certain evidence. Their strike is about N35º- 40ºE, while they dip to the east. This fault strike was also met in the underground works during lignite exploitation activity (Trikalinos & Mousoulos, 1949). It is noted that they also coincide with the tectonic boundary of the Neogene basin in the area. In addition during the lignite excavation works the E-W striking fault system was also found without any surface evidence.

SEISMICITY OF THE WIDER AREA (WESTERN ATHENS)

Before 1900, the seismic history of the wider area of Western Athens, where Peristeri Municipality belongs, shows that the historic earthquakes, which occurred in this area, were strong enough to give intensities equal or higher than VI on the Mercalli scale, were few. More specifically during the time period 1600-1900, the earthquakes which had maximum intensity of ≥VI on Mercalli scale, were five (5). During the 20th century the seismicity of the broader area was high enough but in the strict area no destructive earthquake had occur until September 1999. It was then when that seismic centre at Parnitha Mount reactivated after a long quiet period.

With reference to the seismic risk assessment in the study area, it was revealed that the higher expected (90%) earthquake magnitude at Richter scale for the next 50 years is 6.63R, while the same possibility for the next 100 years is for magnitude 6.67R (Makropoulos, 2001). Stronger earthquakes occur in epicentric distances greater than 50km, thus causing minor damages (as it is known earthquakes of about 6R in a distance of 50km give the same results as an earthquake of about 7R magnitude in a distance more or less 80km.

Furthermore the expected values of the soil parameters, with possibility 90% not to be exceeded the next 50 years, are as follows (Makropoulos, 2001):

- Max soil acceleration 385cm/sec^2
- Max soil velocity 35cm/sec
- Max soil displacement 8,2cm

The valid Seismic Code in Greece (EAK 2000), classifies the Municipality of Peristeri in the zone No I, according to Seismic Hazard Zonation from this Code, assessing a = 0.16 in the equation A=a x g, where A is the soil seismic acceleration and g is the acceleration of gravity. From the above it is clear that the possibilities of seismic hazard in Anthoupolis district of Peristeri Municipality are high, considering the seismic centres in its vicinity, in combination with its rapid and dense urban development, and mainly with the mining activity in the area during the past.

COAL MINES IN ANTHOUPOLI S - A GENERAL APPROACH

The first systematic mining works for the exploitation of the lignite deposits in Peristeri area, started at the beginning of '30s. During the Second World War, Germans exploited the mines more intensively but generally with no rationalistic manner. In 1949 a new Company was established in order to apply intensive exploitation of the mines. According to the studies elaborated at that time, the following were the main remarks (Trikalinos & Mousoulos, 1949):

- The lignite layer presents a thickness up to 5 meters, while 75% of it (3,75m) is pure lignite.
- The formations overlying lignite show excellent stability, at dry and unweathered condition, allowing large openings to be stable for a long period of time.
- The formations underlying lignite consist mainly of clays, and coal bed materials present swelling phenomena.
- Due to tectonic stresses of north orientation, at least one major fault trace was observed.
- Pillars and stall, with removal of the pillars in some cases and collapse of the roof mainly constituted the exploitation method at the beginning. After 1950 the method was changed to the sub level caving.

It is noted that the galleries were opened at the roof of the lignite deposit along three levels, at depths 20-32m, 32-47m and 47-70m respectively. Marinos et.al (2004) refer that the depth of exploitation was limited to 30-90 m. in a rather scattered pattern due to the presence of faults. After 1950, the mining activity was intensified again and resulted in many underground works. This period is also characterized by problems caused during the extended and rapid urbanization of Peristeri area. Soon after, the inhabitants objected to the mines operation and forced the Ministry of Industry to partially close the mines and begin remedial works, at least in the central part of the mines, in order to avoid extended subsidence phenomena, while it was well known that such a hazard was expected to be manifested in the future.

ENGINEERING GEOLOGICAL CONDITIONS

As it is already mentioned, the Neogene sediments of Peristeri – Kalogreza basin are locally covered by (a) fan deposits (mainly in the northern and south western parts of the area, where they mostly are fanglomerates), (b) alluvial deposits and in some locations by (c) recent fills, especially in cases of intensive coalmine activities. Only in the northwestern and southwestern boundaries of the studied area, the basement formations outcrop (Figure 2).

For a better understanding of the engineering geological behaviour of the Neogene sediments in Anthoupolis, which exclusively hospitalise the coalmine activities, the geomechanical characteristics of the various units, which participate in their lithostratigraphy, were studied by using all the existing bibliography (boreholes for coalmine exploitation (Trikalinos & Mousoulos, 1949), boreholes of Athens METRO extension in the area (Kotzias & Stamatopoulos, 1998) and the gained knowledge was completed with a new geotechnical investigation (Rozos et al, 1999). The latter included fourteen (14) sampling boreholes spread in proper location of the studied area, in which SPT, permeability, and, in some of them, cross-hole and down-hole tests were carried out. In Figure 3 the sampling Neogene sediments cores of a borehole (-6) with coal seams (f & g boxes) can be seen.

Based on all the information gained from the above sources, the Neogene sediments were separated into seven lithological types, the usual range of their main physical characteristics and mechanical properties as well as their classification after AUSCS, are given in Tables 1 &2. Their general description is as follows:

Clayey marls to soft marls

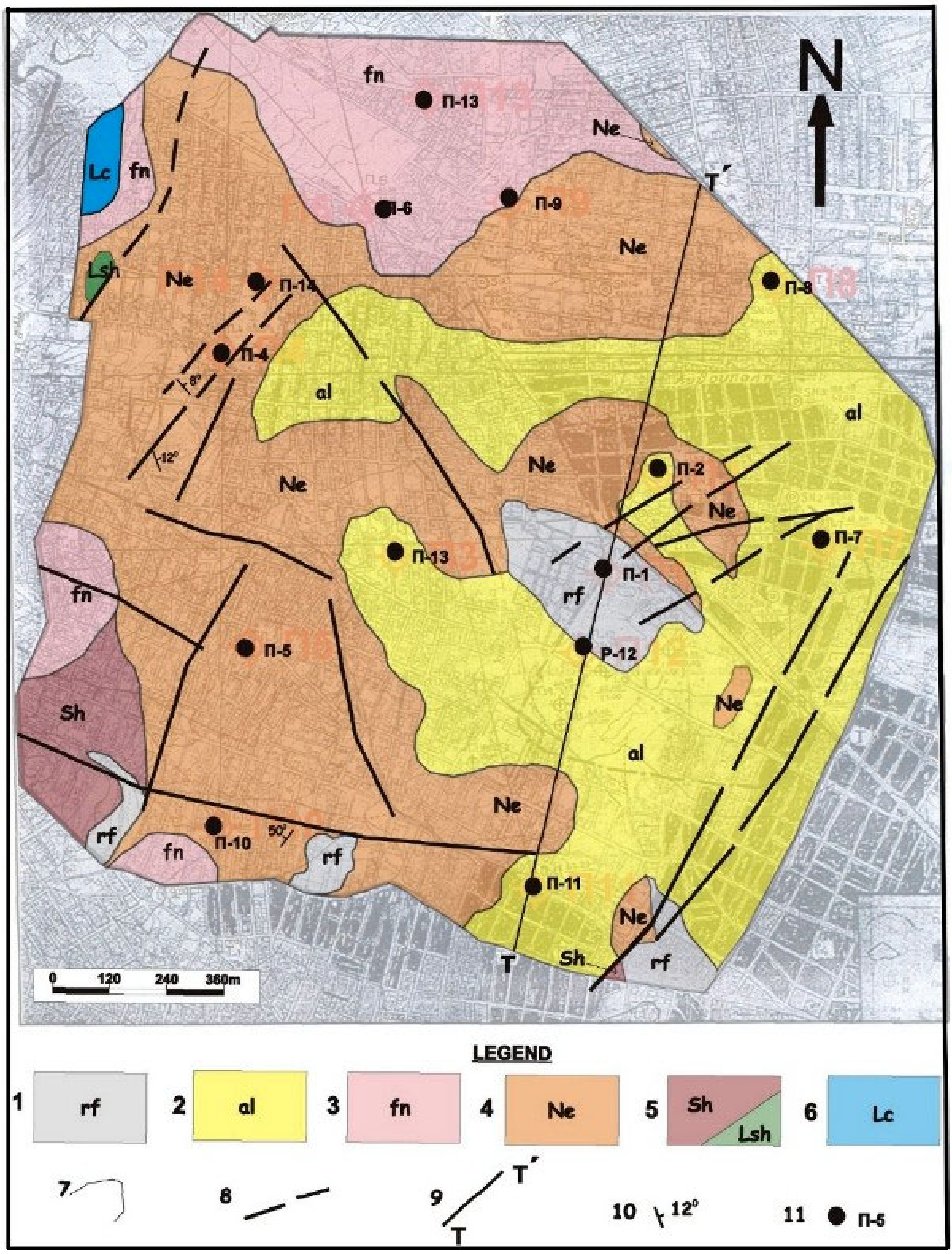
They are alternations of greenish grey to white and or brownish grey marls and light brown to brown clayey marls. This lithological type that dominates at the upper horizons of Neogene sediments, is characterized according to the obtained SPT values as material of medium cohesiveness to stiff material and show a low to very low coefficient of permeability (10^{-4} - 10^{-5} cm/sec, Maag tests).

Stiff to very stiff marls

They are white grey to yellowish brown marls, with calcitic concretions. They are impermeable or present with low permeability (up to 10^{-4} cm/sec, Maag tests), while the SPT values reveal stiff to hard materials.

Calcitic marls to marly limestones

They show a good development especially in the higher morphologically places, while they also participate as distinctive horizons between marls and clayey marls. The white grey marly limestones are usually found as alternations with calcitic marls, reach a thickness of 30-40 cm and locally are fossiliferous. They are characterized by medium to low permeability (k 10^{-2} to 10^{-4} cm/sec, Maag & Lefranc tests), while the SPT values show stiff to hard materials.



1. Recent fills, 2. Alluvial deposits, 3. Fan formations (mostly fanglomerates), 4. Neogene sediments, 5. Athenian schist (flysch like formations and carbonate rocks), 6. Limestones of Aigaleo Mountain, 7. Boundary of engineering geological unities, 8. Faults, 9. Engineering geological cross section, 10. Dip and strike, 11. Boreholes of the recent geotechnical study.

Figure 2. Engineering geology map of Anthoupolis site in Peristeri municipality.

Sandy clayey marls to sandy marls

This lithological type includes brownish yellow to greyish brown sandy marls, friable to medium coherent with angular fracturing. These marls are characterized by medium to low permeability (k *10^{-3}-10^{-4} cm/sec*, Maag & Lefranc tests), while the SPT values show stiff to hard materials.

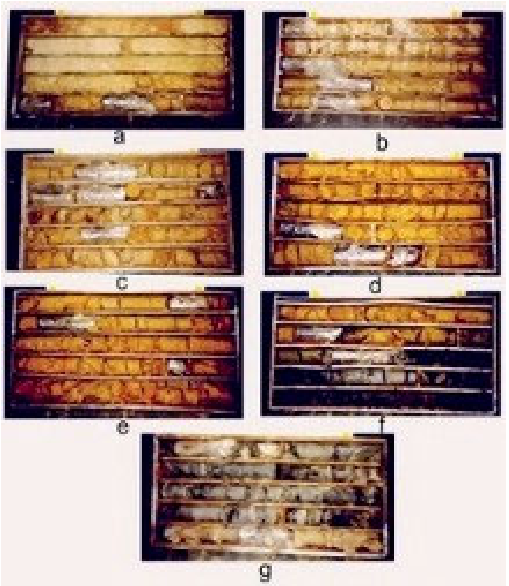


Figure 3. The cores from the -6 sampling borehole.

Diagenetic sands to weak sandstones

They are brownish yellow sands with varying degrees of diagenesis (medium cohesive to very stiff), while locally the diagenesis is very strong and so lens like horizons of brownish yellow to grey fine-grained and rarely of angular-grained sandstones are created. These are very stiff to hard materials which display a medium to low permeability (k 10^{-3}-10^{-4} *cm/sec*, Maag & Lefranc tests)

Siltstones (grey marls)

They are grey in colour marls, which mainly occur in the deeper horizons of Neogene sediments till the end of the investigated depth, with a thickness up to 20m. This lithological type is characterized by low to very low permeability (k 10^{-3} to 10^{-6} cm/sec, Maag tests), while the SPT values reveal very stiff to hard materials.

Coal bed materials

Yellowish brown to grey clayey marls to marls with organics and friable lignite beds alternations, while small percentage of sand and clay also participate. The coal beds usually have a thickness of 10-20cm, but locally they create bodies of considerable thickness (up to 4m). They include intercalations of marls with organics with a thickness of 20-50 cm. Their permeability is low (0,5x10^{-3} cm/sec) while the SPT values reveal very stiff to hard materials.

Table 1. Main physical characteristics of the Neogene sediments in Anthoupoli Peristeri site.

Main lithological types of Neogene sediments	Physical characteristics			Atterberg limits			Grain size analysis			
	Moisture content (w)	Unit weight (γ_b)	Specific gravity (G_s)	LL	PL	PI	Gravels	Sand	Silt	Clay
	(%)	(kN/m^3)		(%)	(%)	(%)	(%)	(%)	(%)	(%)
Clayey marls to soft marls	13.7-35.4	16.0-22.6	16.2-21.8	24-93	16-33	5-61	0.0-14.0	0.0-21.7	49.0-81.0	6.0-57.0
Stiff to very stiff marls	17.0-27.2	21.0-22.4	17.8-22.0	39-87	20-30	16-51	0.0-0.6	0.2-8.0	60.7-87.0	5.0-39.0
Calcitic marls to marly limestones	14.4-46.9	17.5-21.3	26.7-27.4	26-82	16-34	10-74	0.0-11.0	0.7-23.0	47.0-86.0	8.3-34.0
Sandy clayey marls to sandy marls	14.6-22.9	21.5-22.0	26.7-27.0	21-52	14-26	5-35	0.0-6.0	3.0-63.7	40.0-81.0	5.0-36.0
Diagenetic sands to weak sandstones	17.1-17.3	26.6-26.8	26.0-27.0	Non plastic			0.0-2.1	32.6-72.4	17.0-50.0	1.7-16.3
Siltstones (grey marls)	9.9-27.4	17.5-21.6	20.0-24.0	24-76	15-41	8-40	0.0	1.3-18.2	57.4-93.2	2.7-27.3
Coal bed materials	19.5-25.3	19.6-22.0	21.8-24.0	36-45	28-30	6-21	0.0	3.0-15.0	74.0-80.0	11.0-17.0

Table 2. Main mechanical properties and AUSCS classification of the Neogene sediments in Anthoupoli site.

Main lithological types of Neogene sediments	**Uniaxial compressive strength Qu**	**Triaxial test**		**Direct shear test**		**Consolidation test**		**Young modulus, E**	**AUSCS Classification**
		c	**φ**	**c**	**φ**	**Consolidation index (C_c)**	**C_v (at 200kPa)**		
	(kPa)	**(kPa)**	°	**(kPa)**	°		**(m²/year)**	**(GPa)**	
Clayey marls to soft marls	138-384			10-107	12-23	0.050-0.135	0.70-11.44		CL-CH CL-ML
Stiff to very stiff marls	99-185			17-108	12-25	0.070-0.093			CL-CH MH
Calcitic marls to marly limestones	200-30400	51-79	0-22	10-85	10-38	0.070-0.080	1.750-1.851	0.39-1.63	CH-CL
Sandy clayey marls to sandy marls				17-52	20-32	0.075-0.083	0.715-6.894		CL-CH SL
Diagenetic sands to weak sandstones		24-26	40-46	7-40	30-40				
Siltstones (grey marls)	293-39170			6-45	16-40	0.030-0.220	0.920-0.970	0.16-1.63	CL-ML CH-MH
Coal bed materials				108-316	12-35	0.020-0.445			ML

Referring to the materials (crushed mine dirt) which were used for the refilling of the main galleries (adits) and the rest underground works of the coal mine, they are characterized by medium to low permeability (k 10^{-2} to 10^{-4} cm/sec, Maag & Lefranc tests), while the SPT values show dense to very dense materials.

The contribution of the above lithological types to the lithostratigraphy of the studied area up to the examined depth, are shown in the cross sections of the Figure 4.

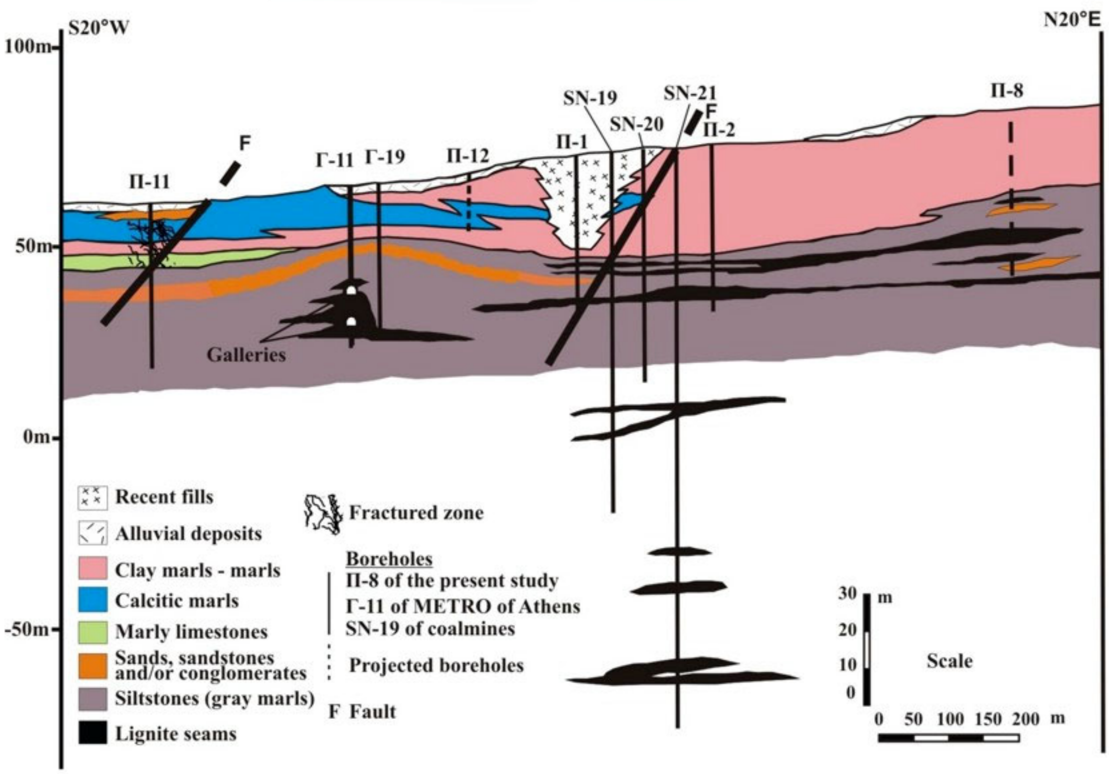


Figure 4. Engineering geological cross section (S20°W – N20°E), showing the various lithological types of the Neogene sediments participating in the lithostratigraphy of the studied area, the coal horizons in the grey marls and the location of the main mining activities (area of thick fills).

Looking at the physical and mechanical characteristics of the various Neogene lithological types from the above Tables, the following main comments can be derived:

- The value of moisture content of clayey marls to soft marls in some cases is above the value of plastic limit indicating plastic behaviour.
- Some of the liquid limit values for three lithological types, namely the clayey marls to soft marls, stiff to very stiff marls and calcitic marls to marly limestones are so high, revealing the presence of swelling clay minerals.
- The consolidation index of coal bed materials (clayey marls to marls) shows values that reveal only in rare cases the presence of swelling clay minerals.

Thus, it was thought that a detailed mineralogical examination of some main Neogene unities would be necessary. For that reason, some representative samples with a high percentage of fines were chosen and examined using x-ray diffraction and infrared spectrometry. The results are given in the Table 3. From these results, which confirm the presence of swelling minerals, it is concluded that: (a) calcitic marls show a rather small amount of swelling minerals, and mainly consist of calcite, (b) stiff to very stiff marls and clayey marls to soft marls present an amount of clay minerals, among of which, the swelling minerals (9-11%) show a percentage which is higher in comparison to the same minerals of other unities and so they are more sensitive in water action. Therefore, in the parts of coal mine galleries that were opened in these sediments and are now almost full of water with fluctuation of its table, the presence of such clay minerals contribute to the deterioration and destruction of galleries support and facilitate the migration of the cavity up to the surface.

SUBSIDENCE PHENOMENA

The occurrence of failures in Anthoupolis coalfield site is a regular phenomenon. The differentiations in manifestation time is a result of participation of many parameters, such as the geomechanical behaviour of geological formations, the hydrogeological conditions, the kind and the depth of exploitation of coal beds, the type of support of underground works, the type of back filling (solid packing) if there is one, etc. So in Anthoupolis district there are places where subsidence phenomena manifested in the past, while there are other places where failures of structures from subsidence take place even today with serious results. Examples of synchronous damages are those in the garage and machine factory of Peristeri municipality and in some houses, in one of which the damage was so severe that it was evacuated.

Table 3. Results of mineralogical analysis of the main lithological types of Neogene sediments, from the study area.

Main unities	Depth of sampling (m)	Montmorillonite %	Mica group %	Chlorite %	Feldspar %	Calcite %	Quartz %
Clayey marls to soft marls	7.50	10.7	37.1	26.0	3.5	11.5	11.2
Stiff to very stiff marls	6.00	8.9	25.0	28.5	3.4	23.9	10.3
Calcitic marls	8.00	3.8	3.8	0.0	0.0	91.9	0.5
Calcitic marls	15.00	5.5	0.0	0.0	0.0	93.2	1.3
Siltstone (grey hard marls)	38.70	1.7	14.0	22.8	12.7	26.6	22.2

The failures which are manifested in Anthoupolis site and affect pavements, buildings and other constructions, were recorded and grouped, according to field observations on ground and constructions, as following:

- Failures that were observed along the contact of two structures as a separation with a uniform width or a bigger width near the roof of the buildings.
- Failures on the pillars and beams on some buildings or transverse cracks on the balconies of the buildings. They are rare at any rate and occur only in some locations, but are the most serious for the structures.
- Cracks on the brick walls. They usually occur near the windows and doors, with a width of 2-7mm, either crossing each other or in a ladder like arrangement.
- Small cracks in the contact of beams – pillars and brick walls of the buildings.
- Failures in the form of cracks on fence walls, on road pavements etc.

The mechanism and action of subsidence phenomena in the studied area

The failures in Anthoupolis site are observed as ground displacements with big length and a comparatively small width. These dimensions are larger than the typical underground works in every case. All of the above agree with the general description of a subsidence in such formations with underground exploitation.

According to existed bibliographic data, the exploitation of Anthoupolis coalfield was done with the pillar and stall methodology. In that case the subsidence phenomena, which are manifested in the surface, are connected with a large number of parameters and that is why, the interpretation of manifestation mechanism and the prediction of their further evolution are particularly difficult.

Some of these parameters are:

- The lithological conditions (mineral composition, natural condition of the formations, discontinuities, etc), the geomechanical behaviour and the hydrogeological regime in the site.
- The geometry and the depth of the galleries and mainly the width of them. As there are three levels of exploitation the above are not so easy to be clear.
- The thickness and the inclination of the lignite beds. These are also difficult to be evaluated now, as either the thickness or the inclination present continuous changes.
- The angle of draw or limit angle. The value of this parameter in Greek territory is taken 45º for the type of weak rocks such as those, encountered in the study area.
- The support method (if any) and the deterioration of the workings.
- The time

From these parameters the lithological conditions, the hydrogeological regime, as well as the geomechanical behaviour of the formations involved in the problem was examined in detail and clarified, while the geometry, the type and depth of the underground works along with the characteristics of lignite beds and the angle of draw were studied from the existed bibliography. It should be noticed at this point, that as it is known, the exact subsidence rate and the extension of subsidence zone above well-studied underground excavations, could be well determined only when the coal bed is almost horizontal and the lithological conditions are uniform. From what has already been discussed, in Anthoupolis site neither lignite beds are horizontal nor the engineering conditions are uniform.

Examining a series of air photos in the area, from 1945 up to 2000, and taking into consideration the field observations, it can be said that the vertical ground displacements on the surface are much smaller than those at the depth of the underground works, while their extent is larger, affecting a wider area on the surface. It is pointed out that the backfilling helped the elimination of the ground displacement in the central part of main coal mining activity.

Also, buildings founded near the edges of troughs of the affected zone are suffered by compressive and tensile stresses. It is noticed here that the horizontal strain caused by subsidence in a building is concentrated in one location and riches up to 0.8% for shallow workings, but more commonly they are 0.2% or less (Tomlinson, 2001).

From the above it is obvious that the exact determination of the mechanism and the real surface action of subsidence phenomena in an old exploitation field is rather impossible. Thus, examining the possible evolution of subsidence phenomena in Anthoupolis site, the causes, which are responsible for them, were determined, using the information gained from the above-referred study. These causes, which are connected with the collapse of a gallery support or roof, are:

- The reduction of physical and mechanical parameters of the mass of the geological formations. As it is expected, under the exploitation procedure, the Neogene sediments in the environment of the underground works (mainly marls) have been loosened and so they easily undergo weathering and erosion processes from ground water action. This action is more intense, as the galleries, which are usually flooded, even in the upper exploited horizon, some times become dry due to ground water table reduction. At this case, the buoyant support of the overburden Neogene sediments is removed and also the wooden support of the galleries is faster deteriorated. In addition to the above the presence of swelling clay minerals cause an internal swelling pressure to be built up which, in turn, reduces the effective stress in the formation and therefore reduces its shear strength.
- The rapid urbanization of Anthoupoli district imposes an additional load, as the upper exploited horizon of lignite beds is only 20 meters beneath the surface. This load causes breakdown in the roof of the underground works at places, contributing to the local manifestation of subsidences.

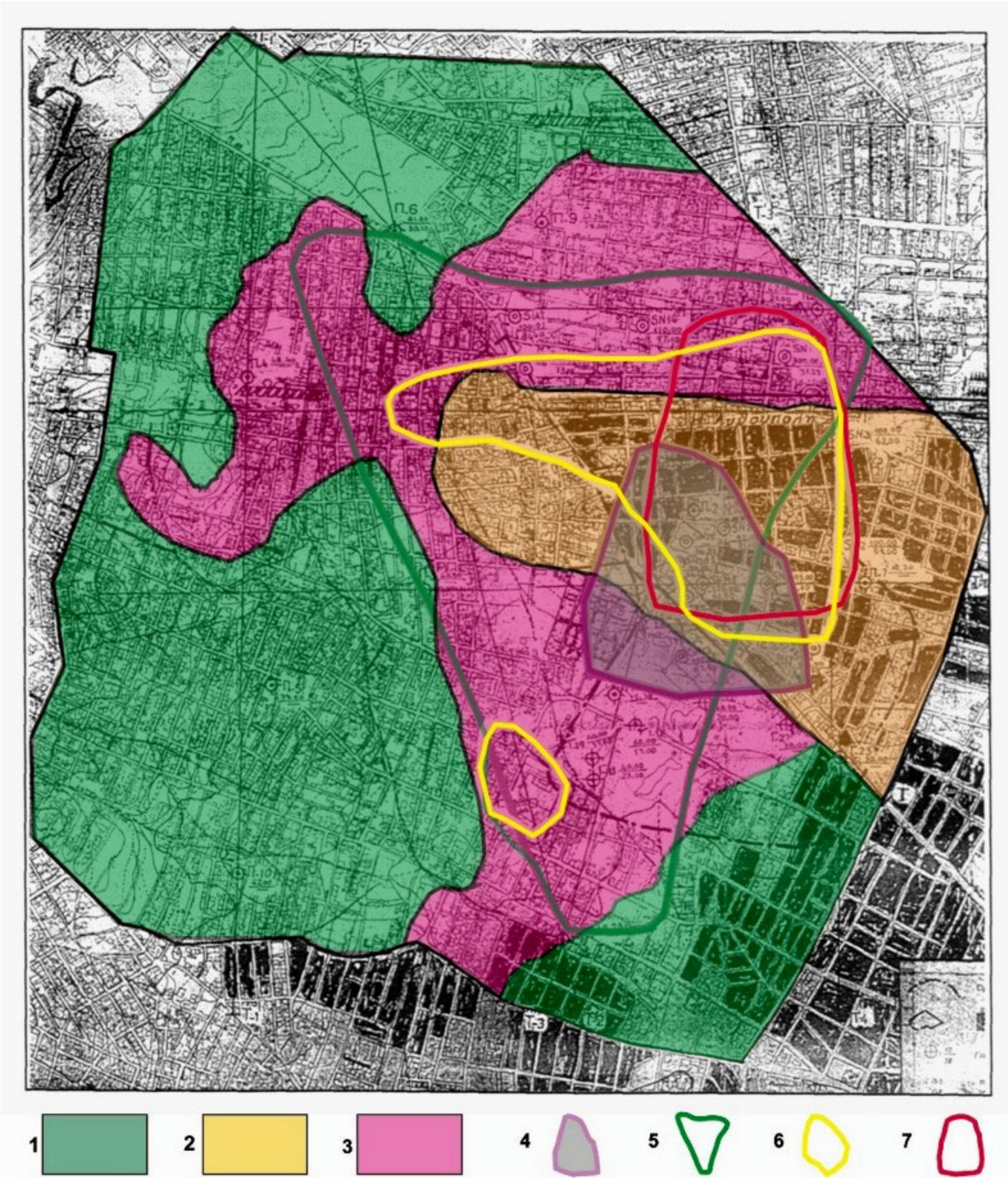
Even if those causes seem to be the most representative according to the information gained for the area, however the lack of complete knowledge about the underground galleries network and their present condition, make impossible the full clarification of the mechanism and the action of the subsidences. Thus in Anthoupolis coalfield, every intervention for stopping of possible future subsidence manifestation is impossible and so intense efforts should be turned to the direction of the protection of new structures in the area from the consequences of the subsidence phenomena.

Zonation of the area according to subsidence risk assessment

For the protection of new structures in Anthoupolis coalfield site from the consequences of subsidence phenomena, a zonation map of the area according to subsidence risk assessment was thought to be necessary. This was done taking into account, the exploitation method, the existing diagrams of the mineshafts and galleries, the accepted value of angle of draw for Greece, as well as the knowledge with regard to the geomechanical behaviour of the geological formations participated in the area as this was gained form the previous comments and discussions. Thus, the influence zones in the surface of the failures of mining works were determined.

Thus, based on the construction damages in the studied area, the existed data for the lignite exploitation activity along with the knowledge about the geomechanical behaviour of the formations gained from the site investigation, Anthoupolis site was distinguished into three zones according to subsidence risk (Figure 5). It should be noted here, that the land filling of the known shafts and galleries considerably reduces the dimensions of the subsidence phenomena as land fill materials show a rather good compaction at least wherever they met with the site investigation works (drilling program).

- The first zone (zone I), includes the north and west part of the examined area where the presence of underground exploitation activity is not likely to exist. This means that in that area subsidence phenomena had not manifested so far and it is unlikely to be observed in the future. Any damage of the constructions in this zone is caused by other factors, rather connected with the kind of construction the type of foundation etc.
- In the second zone (zone II), the known coal mine shafts and adits have been back filled and so the possible subsidence hazard in the area is expected to be of a low intensity and of a small scale. Only damages on buildings of small extent had been noticed in the past, but new and of a large extent phenomena are not expected. This is because the back filling restricted the voids, the migration of which should have already been completed, as the thickness of the overburden sediments is small. Some reserves are preserved for exploitations that either were unknown during the period of land filling and their roof has not collapsed so far, or their back filling was thought not purposeful.
- In the third zone (zone III), areas are included where subsidence phenomena with damages to buildings had been observed in the past, are observed in the present and will be observed in the future, with high intensity, without any possibility of precise prediction. This zone occupies three different parts of the studied area, where there are no known underground works and so land filling has not been done. But it is almost sure that there were exploitation activities, as: (a) this zone surrounds the absolutely known exploitation area, (b) lignite beds were found from the drilling program in similar depths of the well known exploitations, and (c) back fills were found below intact sediments, in a sampling borehole drilled in that area. Therefore, this zone is the most affected and so, some remedial measures should be applied for the existed buildings, along with the new foundation rules for the future constructions.



1. Zone I. In that zone subsidence phenomena had not manifested so far and it is unlikely to be observed in the future, **2. Zone II**. In that zone the known coal mine shafts and adits have been back filled and so the possible subsidence hazard in the area is expected to be of low intensity and of a small scale. **3. Zone III**. In that zone subsidence phenomena have manifested, are observed and will be observed in the future, with high intensity. **4.** Possible limits of the main coal mine activities, **5.** Possible boundary of the upper exploited coal horizon (+50m to +20m), **6.** Possible boundary of the intermediate exploited coal horizon (+10m to -30m), **7.** Possible boundary of the deeper exploited coal horizon (-30m to -50m).

Figure 5. Map of subsidence risk assessment in the study area (Anthoupoli site).

The remedial measures for the subsidence phenomena confrontation should focus either on restoration of the damages in the existing structures or on the protection of the future structures.

The existing structures should be periodically checked as the subsidence phenomena are in a dynamic evolution and it is very possible to be observed in the future with damages in the buildings. For the serious cases which are going to be arisen from this periodical inspection along with the static sufficiency of the construction, the control of the conditions of the foundation is thought to be necessary, for its reinforcement with a proper method.

For the future constructions in the area, beyond the geomechanical behaviour of the foundation ground, the consequences of a possible future subsidence manifestation should be taken into account. The confrontation of subsidence consequences should be based on the thought that damages are in a close relation not only with the intensity and extension of ground deformation but also with the shape and the size of the construction, the maximum vertical displacement as well as with the orientation of the building with regard to the development of the subsidence depression. Therefore, long constructions should be avoided as well as buildings with deep foundation. Also gaps should exist between constructions and yard concrete coverage, as well as in long walls. For the elimination of the problems in the two zones (I & II) with expected problems from subsidences manifestation, as the whole galleries network is unknown, methods such as (a) filling the voids either by sand (hydraulically) or other suitable material (pneumatically) as well as by grouting, via boreholes from the surface, (b) using reinforced pile foundation, is rather impossible (Bell, 1999). The only solution in such a case, even expensive, is the flexible raft foundation (massive concrete slab), founded near to surface.

A proper antiseismic protection of dense urbanized Anthoupolis district, due to increased seismic risk, was thought to be necessary, as it is located near areas with high seismicity. This could be done by means of a Mikrozonation study, which was proposed through the geotechnical study and has already been carried out by IGME (Engineering geology dept. of IGME, 2001) for local authorities.

CONCLUSIONS

Taking into account all the above observations, results of geotechnical study and discussion, the following conclusions can be derived, with regard to subsidence phenomena in Anthoupolis district:

- The broader studied area is a part of Peristeri – Kalogreza Neogene basin and constitute of Neogene sediments, fan and alluvial deposits, which cover the bedrock Mesozoic formations (Athenian schists and limestones). Recent fills locally cover Quaternary formations and Neogene sediments, while lignite beds are encountered in the latter. The tectonic reactivation of the main fault systems, after the sedimentation of the Neogene, has affected the sediments, which are fractured, making the stratigraphy of the Peristeri – Kalogreza basin with lignite beds more complicated.
- The exploitation of the lignite beds in the examined site was done at least in three levels between 20 and 90 meters. Unfortunately, all the underground works were not recorded and so the back filling that was carried out in the lignite mines included only the site of the main exploitation activities and in a manner that restricted but not eliminated the action of subsidence mechanism.
- Regarding the lithological conditions they reveal that construction failures, which had been observed in the past or are manifested even now, are the results of subsidence phenomena taking place due to deterioration of mine galleries for lignite exploitation. The differences in the subsidence manifestation time are a result of many variables and so there are places affected in the past and places that construction failures take place now with impressive results.
- As main causes of the manifestation of subsidence phenomena should be considered the deterioration and the subsequent collapse of the galleries support and also the migration of the cavities to the surface because of the small thickness of the upper exploitation horizons. These phenomena are impossible to be predicted, as (a) the old underground exploitations were made without any record. Thus, the real extent of the underground works, the exact types of excavation, the real physical condition of the formations, the ground water regime, etc are unknown. (b) The back filling was restricted only in the central part of the lignite exploitation.

It is clear from the above discussion, that the exploitation conditions (depth and dimensions of the galleries), in relation with the variability of the overburden formations, make the forecast of the places where similar subsidences and building failures will manifest in the future, impossible.

Based on the results of the engineering, geological investigation and the examination of the construction failures, a zonation map of the area according to subsidence risk assessment was compiled in order to define the areas with serious problems. Three zones of differentiation of damages intensity were distinguished and the frame of the proper remedial measures was proposed.

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