Geotechnical characteristics of the formation of "Tourkovounia" Limestones and their influence on urban construction - City of Athens, Greece

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Abstract: All the hilltops of the city of Athens are occupied by the formation of "Tourkovounia" Limestones. Some of the most important monuments in the city and also many residential areas are founded on these formations. The world renowned monument of Acropolis, the ancient Supreme Court (Arios Pagos), and the Pnika are prime examples of monuments founded on these limestones. A detailed knowledge of the geotectonic data and geotechnical characteristics regarding these formations are clearly important for construction work in these areas.

From the evaluation of engineering-geological maps and tectonic data, from both recent and older studies, it can be determined that these formations are intersected by faults, mainly normal, which in some locations have been subject to intensive karstic weathering. This weathering turns those faults into wide karstic fissures. The karstic voids formed by this mechanism are often 0.5 to 2 m wide and can be infilled or partially infilled with clay or stalagmitic materials. When the karstic fissures intersect the voids can get extremely wide and in some places the voids were up to 15m across. The influence of Karst structures on the geotechnical behaviour of the limestones is significant and this must be taken into account at design stage.

This paper aims to present data regarding the engineering geological setting and properties of the Tourkovounia limestones. In particular, the paper presents data about the stress field that caused the main neotectonic structures, the distribution and the geotechnical characteristics of the karstic fissures, the orientation and the geometry of the joint sets and finally the geotechnical parameters of the limestones.

Résumé: Toutes les collines de la ville d'Athènes affleurent les calcaires de "Tourkovounia". Acropolis, Arios Pagos, et Pnika, des monuments très connus ou monde entier, sont des exemples caractéristique, comme ils sont fondés sur ces calcaires. Ainsi, il est évident que la connaissance des données tectoniques et des caractéristiques géotechniques de ces calcaires est importante pour les projets des constructions.

L'évaluation des cartes techniquo - géologiques et des données tectoniques dérivées par des études précédentes, a donné que ces calcaires sont affectés par des failles normales en principe où par endroit on peut observer une érosion karstique intense. La désagrégation karstique intense transforme ces failles en ouvertures karstiques larges. Les dimensions de ces karsts formés par ce mécanisme, sont de 0.5m à 2m où on peut trouver des stalagmites ou du matériel d'argile. Quand ces ouvertures karstiques se croisent les espaces vides karstiques deviennent très larges et leurs dimensions par endroit dépassent les 15m. C'est évident que l'influence de ces structures au comportement géotechnique des ces calcaires est grande et on doit en tenir compte aux projets de constructions.

Le but de cet article est à présenter les données techniquo – géologiques des calcaires de Tourkovounia et plus précisément les tension néotectoniques, la distribution et les caractéristiques géotechniques des ouvertures karstiques, l'orientation et les paramètres de groupe de diaclases parallèles, ainsi que les paramètres technique – géologiques des calcaires.

Keywords: geology of cities, limestone, bearing capacity, slope stability, risk assessment.

INTRODUCTION

Athens is a major city with intensive construction activity. Data regarding the geotechnical characteristics of the formations occupying the foundations of the city are extremely valuable. "Tourkovounia" limestone is a member of the upper calcareous horizon of the Alpine formations. Although that the Tourkovounia limestone only covers a small percentage of the total area of Athens, the knowledge of the geotechnical characteristics of the formation is important. Some of the most important ancient monuments, many recreation sites and many residential areas are founded on these formations. The monuments of Acropolis, Arios Pagos and Pnika, the recreation sites of Likavitos and Attiko Alsos Park are prime examples of sites founded on these limestones.

The findings of the paper are based on the data collected during the geotechnical study of the stability problems that have occurred on the slopes of an inactive quarry on Tourkovounia Hill (Karfakis J. & Loupasakis C., 2005) and it is supplemented by information collected through an extensive literature search. During the last decade, this quarry was turned into a park ("Attiko Alsos" park) and as a result of the stability problems, concerns arose for the safety of the infrastructure and park visitors (Figure 1).

The objective of the paper is to present data about the geological and neotectonic settings together with the geotechnical characteristics of the Tourkovounia Limestones. The paper also aims to summarise the main geotechnical problems with the limestone that arise due to the intensive fracturing and karstification of the normal faults.

Figure 1. Aerial photograph of Tourkovounia hill. The "Attiko Alsos" park is located in the SE section of the hill. This park consists of a public garden, an open air theatre, a volley-ball and a basket-ball field, a coffee-bar and an extensive parking area. This figure presents some of the normal faults which, in spite of the intensive alteration of the morphology, are visible in the aerial photograph. The covered extensions of those faults go across the built-up area located on the top of the hill and under the foundations of the houses.

GEOLOGICAL SETTING

The geological setting of the Athens area has been studied by many researchers since the middle of the 18th century (Lepsius R., 1893, Kober, 1929, Marinos & Petrascheck, 1956, Tataris 1967, Nibermayer 1971, Marinos et.al. 1971, Trikallinos 1955, Paraskevaidis & Chorianopoulos, 1978). In spite of that, the knowledge about the lithostratigraphic structure of Athens is incomplete.

In Athens, the "Tourkovounia" limestones and, generally, the upper calcareous horizon are the upper members of the known lithostratigraphic series of the Alpine Formations. The age of the upper calcareous horizon was determined to be Upper Cretaceous (Cenomanian - Turonian). These limestones overlie a marly horizon which lies over the Athenian schist. The marly horizon consists mainly of hard arenaceous marls, with thin marly limestone intercalations. The Athenian schist consists mainly of alternating beds of sericite sandstone, shales and phyllites, locally with intercalations and lenses of crystalline, usually microclastic, limestones (IGME, 1982, 1986, 2002). Thin breccio – conglomerate beds are usually located along the base of the limestones.

According to the majority of the researchers (Negris, 1913, Kober, 1929, Marinos & Petrascheck, 1956, Trikallinos 1955, Nibermayer 1971 and others) the upper calcareous horizons were overthrusted over the marly horizon and the hilltops of the city of Athens were deposited in form of big olistoliths. According to that theory the breccio – conglomerate beds, located along the base of the limestones, are tectonic mylonites.

The "Tourkovounia" limestones are named after the Tourkovounia hills but they are not located only within the narrow geographical limits of those hills. These limestones are members of the upper calcareous horizon and although that the several geological maps of Athens refer to them with different names, or group them dissimilarly with the limestones of the surrounding mountains (Niedermayer J., 1971, IGME, 1982, 1986, 2002), many researchers note that these limestones occupy all the hilltops of the city.

The "Tourkovounia" limestones are light to dark grey, thickly bedded to massive and occasionally medium bedded, recrystallized, karstic and intensively fractured. Also, limestone breccia intercalations are located at their upper parts.

TECTONICS – STRESS FIELD

From the evaluation of the data collected during the engineering – geological mapping of the inactive quarry on Tourkovounia hill came out that the "Tourkovounia" limestones are fractured mainly by normal faults. The projection of the tectonic data, coming from thirty one (31) normal faults, on a directional rose diagram (Figure 2) and on a Schmidt diagram (Figure 3) determined that the main orientation of faulting is ENE-WSW to SE-NW. Correspondingly, the orientation of the main tensile stress field that generated those fractures is NNE-SSW. The distribution of the main stresses and the procedure applied for the estimation of the tensile stress (sigma 3) direction are presented on the Schmidt diagram of Figure 3.

Figure 1 presents some of the normal faults which, in spite of the intensive alteration of the morphology, they are visible in the aerial photograph of Tourkovounia Hill. Besides the Tourkovounia Hill, major tectonic fractures of ENE-WSW to SE-NW direction are visible on the aerial photographs of Acropolis and Likavitos hills (Figures 4 & 5). This fact confirms that the limestones of the hill tops of Athens were subjected to the same tensile tectonic stress field.

According to bibliography (Andronopoulos B. and Koukis G., 1976) the tensile stress field acted after the overthrusting of the upper calcareous horizons. The overthrusting took place in Lower Tertiary and the direction of the folding axes was NE-SW.

Most of the normal faults exhibit intensive karstic weathering, resulting in wide karstic fissures. These voids are 0.5 to 2 m wide and are partially or completely infilled with clay (Figures 6, 7) or stalagmitic materials (Figure 8). When the karstic fissures intersect the void structures can become extremely wide. In some places structures reaching up to 15m wide were observed (Figures 9, 10).

From the evaluation of the tectonic data collected from the joints, it was concluded that the Tourkovounia Limestone is fractured by numerous joint sets, which are not always related to the stress field that resulted in the major tectonic structure. These joints appear dissimilar in distribution and as a result the discontinuities are variable in frequency. Most of the joints have limited persistence (0.6 to 1 m), wide and random spacing (1-2 m), little or no aperture (< 0.1 mm) and no karstic weathering. The estimated RQD values away from the fault zones are high, reaching 70-80%.

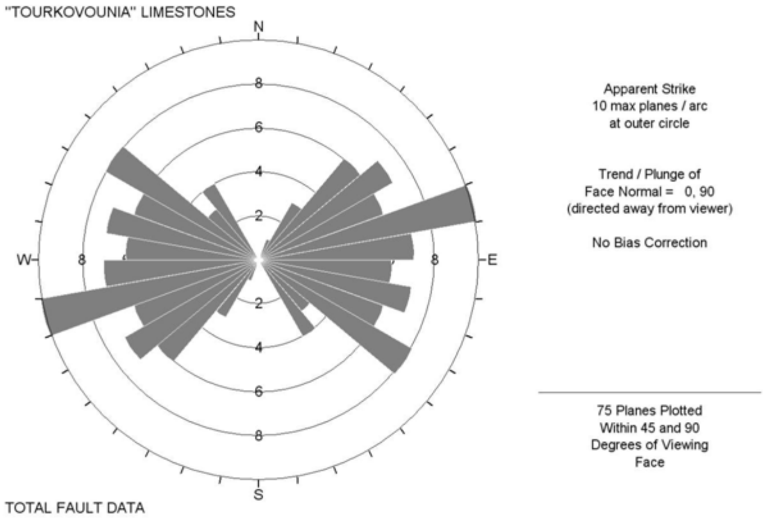

Figure 2. Directional rose diagram of the faults mapped on Tourkovounia hill.

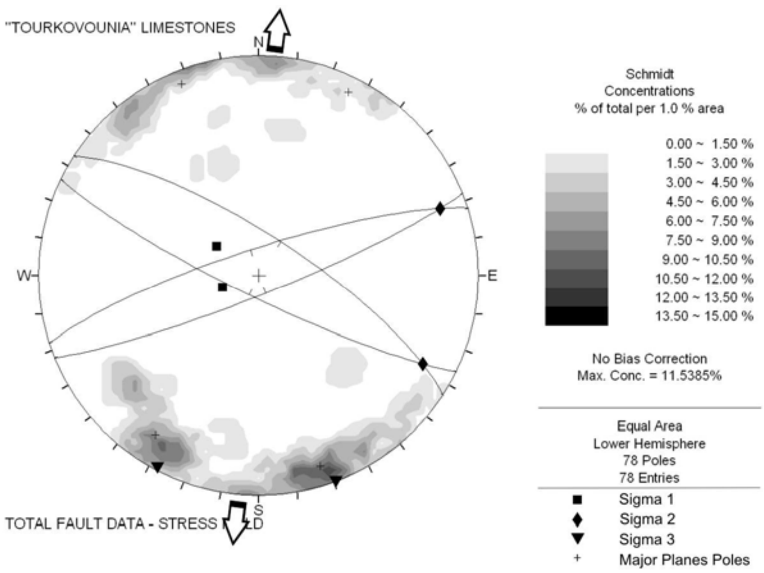

Figure 3. Schmidt diagram presenting the orientation of the main direction of the faults, the distribution of the main stresses and the procedure applied for the estimation of the tensile stress (sigma 3) direction.

Figure 4. Aerial photograph of Acropolis hill. Major tectonic fractures – normal faults of ENE-WSW to SE-NW direction traced on the photograph.

Figure 5. Aerial photograph of Likavitos hill. Major tectonic fractures – normal faults of ENE-WSW to SE-NW direction traced on the photograph.

GEOTECHNICAL CONSIDERATIONS

Although the Tourkovounia Limestone is a formation with excellent mechanical characteristics, the wide karstificated zones along the normal faults represent areas with particular geotechnical difficulties. The main geotechnical issues relate to differential settlements of structures, slope stability of excavations and inflow of water into excavations formed for foundations or underground constructions.

It is obvious that the mechanical characteristics of the clay materials filling the fractured zones are completely different from those of the surrounding limestones. The bearing capacity of the unconsolidated clay materials is much lower than the bearing capacity of the limestones. Without consideration of these variable founding properties, differential settlement of structures or even the failure of the foundation could occur. The problems are likely to be worst along the wide karstificated fractured zones and when one or more footings are positioned completely or partly on the clay materials. Of equal, if not greater, importance could be when a wide karstic void extends below the foundation surface. Overlying material could collapse into the void under the newly applied construction loads, causing the failure of the overlying foundations.

Generally, as a result of the good mechanical properties of the limestones, most structures are founded by the use of spread or combined footings. These types of footings are satisfactory when the rock is fractured and lightly karstificated. However, when the rock is intersected by wide karstificated fractured zones containing small caves, close to the surface, or infilled with clay materials, these footing types could be inadequate and potentially unsafe. As mentioned previously, the fractured zones can be extremely wide reaching up to 15m (Figures 9, 10). Detailed geotechnical studies must be conducted especially when traces of faults or zones infilled with clay materials are located into the construction plan area. The geotechnical studies should include shallow boreholes along the faults in order to detect possible karstic voids.

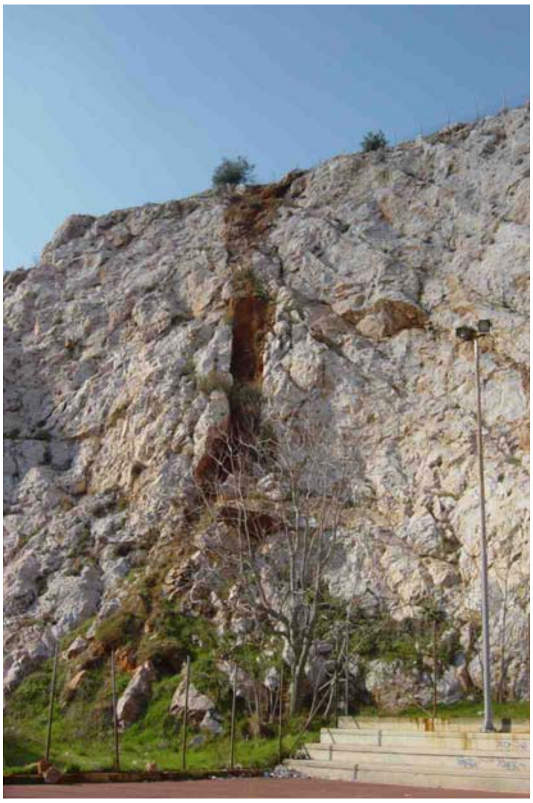

Figure 6. Normal fault expanded by the karstic erosion, filled with clay materials (1.5m wide).

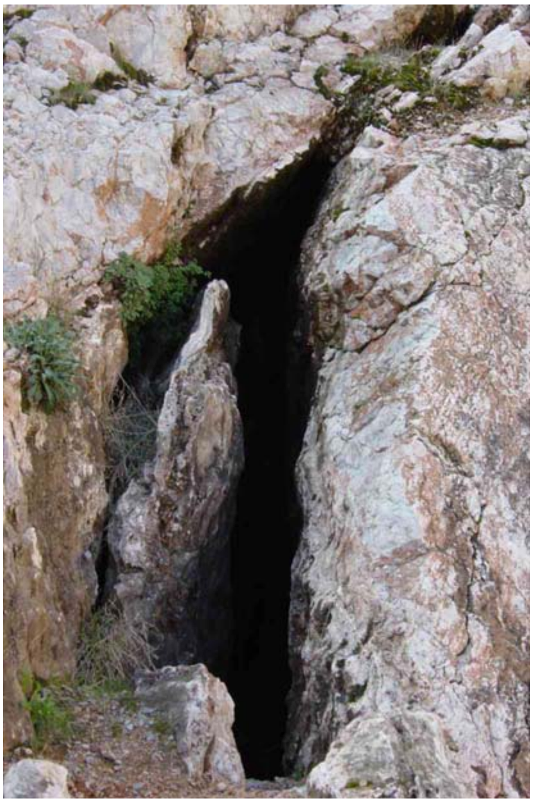

Figure 7. Normal fault expanded by the karstic erosion, partially filled with clay materials (0.5m wide).

Figure 8. Extremely wide karstic void (up to 10 m) – small cave formed along a normal fault.

Figure 9. Extremely wide karstic fissure (up to 15 m) formed along the intersection of normal faults, filled with clay materials. The matrix includes blocks of the "Turkovounia" limestone. During the excavation of the quarry the surrounding limestone was left in place in order to avoid destabilising the infill material.

The infill materials of the fractured zones include blocks of the parent limestone. The blocks are supported in the clay matrix (Figures 8, 9) or lodged into the stalagmitic net (Figure 10). Gradual erosion of the surrounding materials or dynamic loading of the slopes (earthquake) can lead to the releasing of these blocks which end up at the base of the slopes (Figures 8, 10). These slope stability problems should be taken into consideration when the slope is to remain open permanently (e.g. cuttings for roads).

The protective measures required for addressing these slope stability problems are generally relatively simple. In cases of short slopes, the construction of a containment wall a short distance from the base of the slope is often adequate protection for the slope. The height of the wall and the distance of the wall from the base of the slope are proportional to the height of the slope. In cases of higher slopes the containment wall may be combined with netting installed along the fractured zone. Also, in some cases the application of sprayed concrete reinforced with a mesh/net can replace the containment wall.

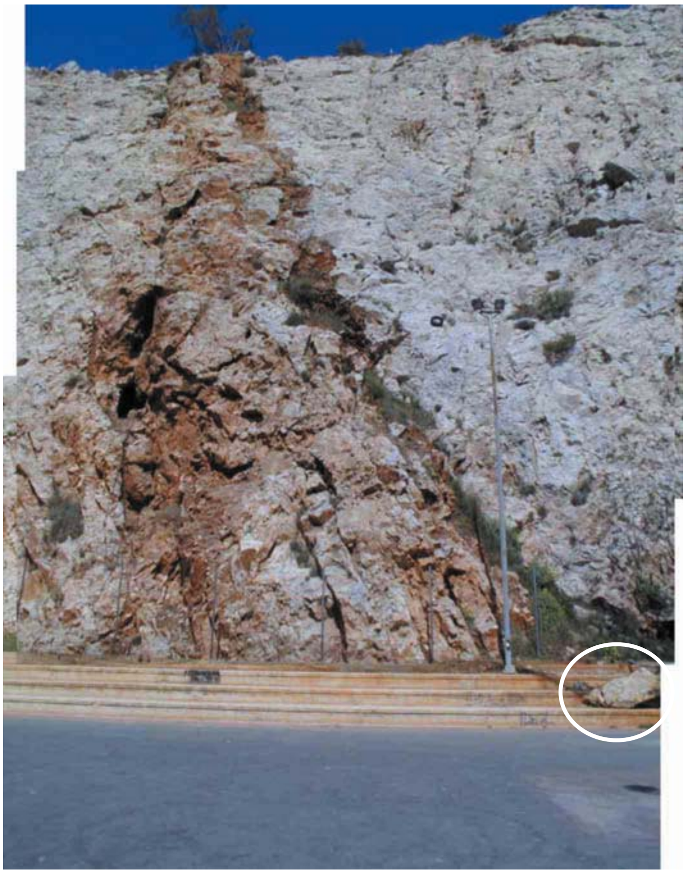

Figure 10. A fractured and karstificated zone (up to 10 m wide). The karstic fissures are partly filled with stalagmitic materials. The large rock block at the base of the slope has fallen from this zone. These rockfalls cause damage to the infrastructure of the "Attiko Alsos" park and it is obvious that they represent a safety hazard to visitors.

As mentioned previously, the "Tourkovounia" Limestones overlie a marly horizon which lies over the Athenian schist; the marly horizon has low permeability. The limestones above are quite different being highly macro permeable formations because of the intense fracturing. The differences in the permeability allow the formation of perched aquifers along the impermeable interface. Small springs flowing from the base of the limestones are located around the hill tops of Athens. As an example, three small springs flow from the base of the limestone below the Acropolis.

The potential of those aquifers is relatively low but small inflows should be expected in excavations constructed close to the base of the limestones. Because of the high permeability values of the fractured limestones those inflows can increase significantly following intensive rainfall. This should be taken into account in order to avoid flooding of excavations or underground constructions.

The geotechnical parameters of the Tourkovounia Limestones were estimated during geotechnical studies, conducted on that formation by I.G.M.E. (Andronopoulos B. & Koukis G., 1976, Karfakis J. & Loupasakis C., 2005). The estimated values of a number of the geotechnical parameters are as follows:

- Dry density, ρ_d: 2.7 T/m^3
- Uniaxial compressive strength of intact rock, σ_c: 45.5 MPa
- Point load strength index, $I_{s(50)}$: 2.52 MPa
- Approximate relation between σ_c - $I_{s(50)}$, k: 18
- Angle of friction of the discontinuity surfaces, φ: 39°
- Dilation angle, ψ: 14 – 16°

CONCLUSIONS

For regions occupied by the Tourkovounia Limestone, the wide karstificated zones that have developed along the normal faults can have a significant geotechnical impact for construction work. In situations where geotechnical studies are incomplete or inadequate, major problems could arise due to differential settlement, slope stability and inflow of water into excavations or underground constructions. As described in this paper, these problems are predictable and can be investigated and addressed at design stage through the execution of a specialist geotechnical study.

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