Implementation of a ground investigation strategy on urban fills

NIKOLAOS CHATZIGOGOS[1], THOMAS MAKEDON[2], STEFANOS TSOTSOS[3] & BASILES CHRISTARAS[4]

[1] *Geology, Aristotle University of Thessaloniki. (e-mail: chatzi5@hotmail.com)*
[2] *Geology, Aristotle University of Thessaloniki. (e-mail: thomas@geo.auth.gr)*
[3] *Civil Engineering, Aristotle University of Thessaloniki. (e-mail: stsotsos@civil.auth.gr)*
[4] *Geology, Aristotle University of Thessaloniki. (e-mail: christar@geo.auth.gr)*

Abstract: The design of major projects in urban areas involves detailed investigation, analysis and correlation of geotechnical factors that determine the design parameters for construction. Thessaloniki is an old historical city of Macedonia, Greece with no less than 2300 years of continuous urban evolution. Furthermore, the special characteristics of the city location, namely the sea front, high seismic activity, and floods, along with continuous human activity, wars and major disasters, have contributed to the formation of an urban environment with highly complex and heterogeneous ground conditions. These include soils formed by natural processes, non-engineered fills formed mainly as by-products of human activity and engineered fills created to serve construction purposes.

More specifically, the factors mentioned above have contributed to the formation of a relatively thick artificial deposit that covers the historical centre and poses an every day problem in urban design and development of this part of the city.

This paper proposes the implementation of a ground investigation strategy that contributes to the determination of the specific geometrical characteristics and physico-mechanical properties of old urban fills. This strategy aims at better understanding of the mechanical behaviour of such fills in the course of construction of major projects of urban infra-structure. On the above basis an investigation of Thessaloniki's urban fills is presented in respect to the development of the transport system of the city.

Résume: Le planning des projets principaux dans des secteurs urbains comprend la recherche détaillée, l'analyse et la corrélation des facteurs géotechniques qui déterminent les paramètres de conception pour la construction. Thessaloniki est une vieille ville historique de Macedoine, Grece, de 2300 ans d'évolution urbaine continue. En outre, les caractéristiques spéciales de l'endroit de ville, près du bord de la mer, comme ils sont l'activité sismique élevée, les inondations, l'activité humaine continue, les guerres et les désastres principaux, ont contribue a la formation d'un environnement urbain dans des conditions au sol fortement complexes et heterogenes. Ceux-ci incluent des sols constitues par des processus naturels, les dépôts non- élabores ont forme principalement comme sous-produits d'activité humaine et ont élabore des dépôts crées pour atteindre des objectifs de construction. Plus spécifiquement les facteurs mentionnes ci-dessus ont contribue a la formation d'un dépôt artificiel relativement épais qui couvre le centre historique et pose un problème continuel dans la conception urbaine et le développement de la présente partie de la ville.

Cet article propose l'exécution d'une stratégie de recherche du sol qui contribue a la détermination des caractéristiques géométriques spécifiques et des propriétés physiques et mécaniques de vieux dépôts urbains. Cette stratégie vise un meilleur arrangement du comportement mécanique de tels remplit au cours de la construction des projets principaux de l'infrastructure urbaine. Sur la base ci-dessus une recherche sur les suffisances urbaines de Thessaloniki est présentée en ce qui concerne le développement du système de transport de la ville.

Keywords: Backfill, engineering geology, geology of cities, landfill, mechanical properties, soil description.

INTRODUCTION

The term fill is used to describe ground that has been formed by human activity, in contrast to natural soil, which results from geological processes. The terms ‘fill’ and ‘made ground’ are used to describe a large variety of materials covering a wide area, which have been formed by human activities, usually by placing natural soils and rocks or waste material over natural ground. This procedure is resulting in the raising of the level of a location. Fills are generally divided into engineered and non-engineered.

An engineered fill is selected, placed and compacted to an appropriate specification, so that it will exhibit the required engineering behaviour. Engineering design focuses on the specification and control of filling. A non-engineered fill has risen as a by-product of human activity, usually involving the disposal of waste materials. It has not been placed with a subsequent engineering application in view (Charles 1993).

Most problems are associated with urban development on non-engineered fills. In urban locations where there has been continuous occupation of land for centuries, there are likely to be large areas of filled ground. This has happened mainly in historical times, when street levels have risen as a result of the disposal of household refuse, and houses have been rebuilt on the ruins of demolished buildings. These old urban fills may contain soil, rubble and refuse. A lot of engineering problems are associated with the uncontrolled and unpredictable nature of urban fills.

Thessaloniki is an old historical city located in Macedonia, Greece. As with most historical cities, ancient man-made deposits extend throughout the entire historical centre of the city, covering Thessaloniki's natural ground surface. The historical centre is the part of the modern city, which used to be enclosed by the ancient city walls (Figure 1). Despite the fact that most of the old urban fills are of relatively small thickness, Thessaloniki's historical fill has a thickness that in places exceeds 12 m and is very heterogeneous. The problem of mapping and determining the geotechnical properties of this formation is complex. The need for urban development of the area makes the solution to this problem urgent, especially in view of the construction of major proposed projects, such as Thessaloniki's Metro (underground railway).

Geotechnical investigations in urban fills for the purpose of urban development have led to the accumulation of a large quantity of geotechnical data, adequate for the determination of design parameters in small-scale constructions. However, the determination of design parameters for large-scale projects in urban fills still seems a very difficult task. This is due to the variability of the geotechnical data available and the heterogeneity of the fills with regard to large-scale projects, which make their interpretation almost impossible. Therefore, emphasis should be given to the determination of the age, the origin and nature of the materials, as well as the methods of placement of the various subparts of every fill. The determination of these factors can lead to a general classification method, which can serve as a basis for the design of more sophisticated geotechnical investigations for the interpretation of the data.

The implementation of the above mentioned strategy is carried out for Thessaloniki's urban fill, which consists of materials of various origins. The diversity of materials results not only from the continuous land use of the area for more than 2000 years but also from its geological background that has produced a large variety of soils and debris material. The geomorphologic and geographical setting of the city has also contributed to the significant thickness of this formation.

LOCATION AND SETTING

Thessaloniki is located in northern Greece in the region of Macedonia. It is one of the oldest cities in Europe (founded 2300 years ago); it is the capital of the region of Macedonia and the second largest city to Athens in Greece. The urban area of the city stretches over 12 km in a bowl-shaped zone enclosed by low hills that face a bay opening to the Thermaikos Gulf. The city extends in a general NW-SE direction in the Thermaikos coastal zone and sits between the Hortiatis mountain, the Oraeokastro hills (N-NE) and a broad plain formed mostly by alluvial deposits from the Axios and Gallikos Rivers (Figure 1). The topography of the city starts from sea level and reaches an elevation of 100-150 m with smooth ascents.

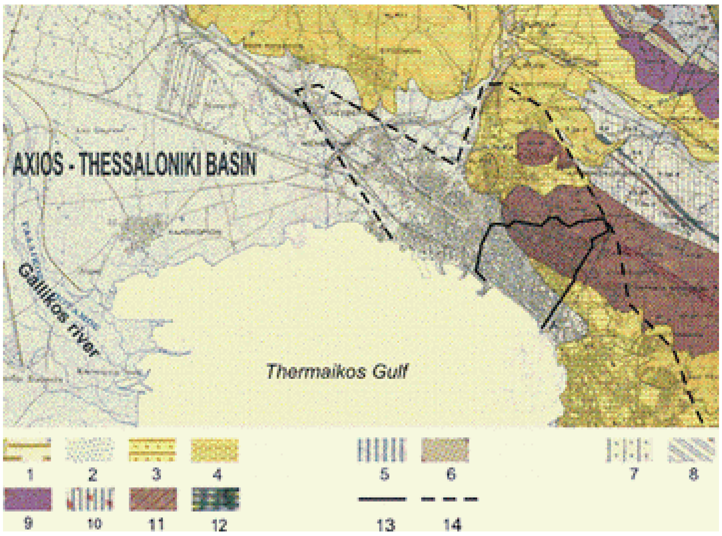

Figure 1. Geological map of Thessaloniki area: Holocene: 1. Lower stage of lowest terrace system (sand, gravel, red clay, conglomerates. 2. Holocene deposits undivided. Neogene: 3. Sandstone-marl series 4. Red clay series. Lower-Middle Jurassic (?): 5. Sandy shales. Middle-Upper Triassic: 6. Limestone. Triassic-Middle Jurassic: 7. Calcareous flysch. 8. Phyllites. Upper Jurassic: 9. Gabbro. 10. Quartz veins. Mesozoic: 11. Leucocratic albite-sericite-microclinic gneiss, epigneiss, green schists. 12. Ultra-maffic rocks. 13. Historical city centre. 14. Urban expansion of Thessaloniki.

Thessaloniki is located in the Axios geotectonic zone, which is adjacent to the Servomacedonian massif, one of the most seismo-tectonically active regions in Europe. The geological setting of the city can be divided into two major units: The crystalline bedrock, which outcrops at the N-NE part of the city reaching at a depth of 150 to 300m near the coastline in a W-SW direction (Anastasiadis et al. 2001) and the soil formations that overly the crystalline rocks and cover the biggest part of the city. The main formations as seen in Figure 1, (geological map of the area by IGMR) are: The Mesozoic Hortiatis suite consisting mainly of albite-sericite-microcline gneiss, epigneiss and green schists which form the crystalline bedrock and the Neogene deposits consisting mainly of sandstone marls and red clays. These underlie recent deposits of Holocene age (clays, sands, pebbles). The coastal zone is formed of both naturally deposited loose material and artificial deposits, which cover a big area at the centre of the city (Figure 1).

The city of Thessaloniki is strongly affected by seismic activity that takes place in the wider region. Numerous earthquakes have occurred mostly connected to movements of the lithosphere of Axios Zone, with a predominant northwest radiation direction (Papazachos 1981). According to historical data, 25 events in the last 17 centuries have caused severe damage to the city of Thessaloniki. During the 20th century alone, eight shocks have occurred in the Servomacedonian Massif with magnitude M≥6.5. The most recent seismic event was the June 20, 1978 earthquake of magnitude M=6.5. It was the strongest motion out of a series of more than 100 earthquakes. The epicentre lies east of Thessaloniki in the region of lakes Volvi and Langada. From historical records it is seen that damaging earthquakes occurred during 7th century AD and again in 1635 and 1839. This long seismic record, in conjunction with the activity of the 20th century (1902-1905, 1921-1933, 1978) may lead to the conclusion that the region is characterized by rather strong earthquakes that have mean recurrence periods of about 40 years and have an extended period of aftershock activity, a pattern that distinguishes the region from the other seismic zones of Greece.

INVESTIGATION AND GEOTECHNICAL ASPECTS

Natural coastline

The ground in the historical centre can be divided into three zones (Tsotsos et al. 1988). Zone I is the bedrock appearing at the surface. In zone II the bedrock is covered by the red clay series, which are overlain by a cap of fill material. In zone III there is a layer of organic silt present between the red clays and the fill. The majority of the monuments are located in zone II and all of them have rather excessively loaded foundations (Tsotsos et al. 1988). The presence of this layer of organic silt introduces the issue of the location of the natural coastline of Thessaloniki. This is the criterion for a primary classification of Thessaloniki's fill based upon its age, its method of placement and its origin of materials (Figure 2).

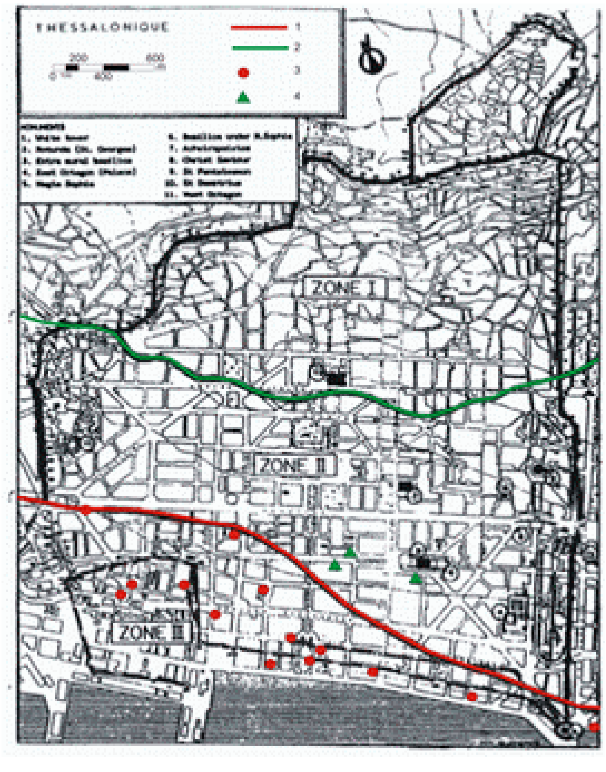

Figure 2. Map of the historical centre of Thessaloniki (after Tsotsos et al. 1988). 1. Natural coastline, 2. Zone I – II boundary, 3. Boreholes where organic silt was found, 4. Boreholes where organic silt was not found.

It is assumed that this layer was formed by degradation of plants of the old seabed in saturated conditions. This took place after the demolishing of Thessaloniki's south city walls in 1866 and the expansion of the coastline southwards by backfilling. Figure 2 also indicates the locations of boreholes where this layer was found and of those where it was not found. Based on the above assumption, the line that separates the boreholes on the basis of the presence or absence of the organic silt represents the natural coastline. This agrees with the historical evidence of the location of the old port of Constantine the Great. Furthermore, if the above assumption stands then the bottom of the fill inside boreholes located south of the proposed natural coastline, should be found below the present sea level. This was indeed verified by the examination of such boreholes. Figure 3 shows that there are three zones (B, C and D) in the centre of the city with a NW-SE direction, within which, the rate of deposition of fill through time is steady (Christaras 1988).

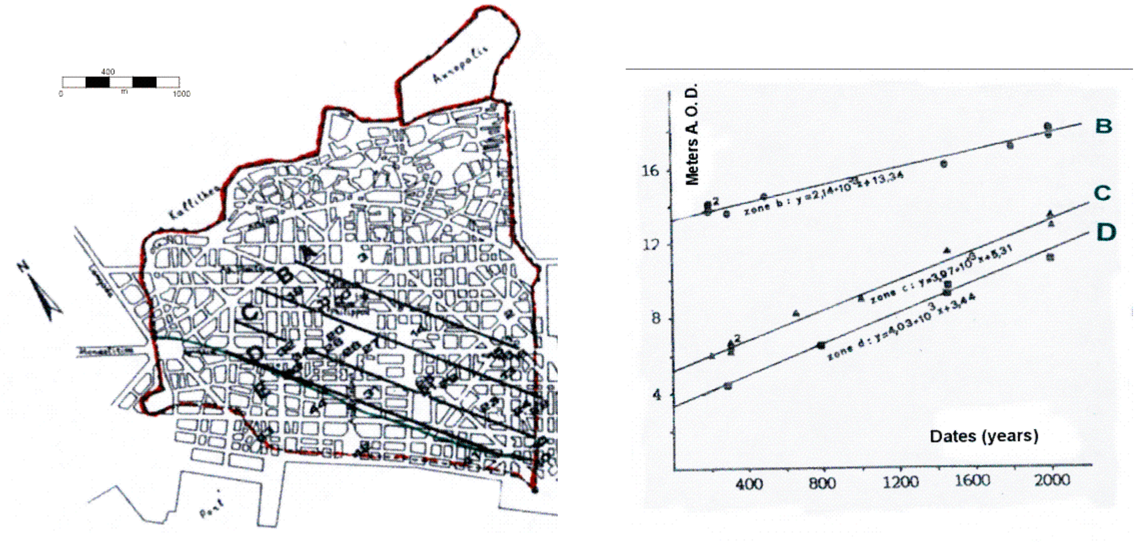

Figure 3. Map of zones of same rate of deposition and relation between the elevation of the floor of monuments and their time of construction in respect to the zone each one of them is located (after Christaras 1988).

The general direction of these zones agrees with the direction of the proposed natural coastline. Actually the southern border of zone D is on the same line of the natural coast as shown in Figure 2. The direction of these zones agrees with the NW-SE direction of the coastline that was assessed on the basis of the presence of organic silt. The higher rate of deposition in zones D and C can be explained assuming that the transportation of materials eroded from the NE hills towards the SW was obstructed by the old fortifications, which formed a 'barrier' to the transportation further south. This assumption is validated by the presence of pebbles of green schist, which outcrops in the northeast part of the city, inside boreholes. In addition to that, archaeological evidence shows that the expansion of the city during the Roman and Byzantine period took place in the same direction. The determination of the natural coastline of Thessaloniki classifies the fill covering the historical centre into two categories. A historical fill over 1500 years old found in Zone II and a recent artificial backfilling found in Zone III.

Thickness of fill

The determination of the thickness of old artificial deposits is of major importance for urban development and especially for the investigation and design of future constructions. In cases where the thickness of these deposits is significant as in the case of Thessaloniki the design of foundations and underground constructions, is a rather complex procedure since most of the buildings of the historical centre are founded on this complex formation. The proposed underground constructions need to avoid this formation not only because it is difficult to accurately evaluate its geotechnical properties and calculate settlements, but also because there is a high possibility of 'hitting' archaeological relics located throughout the fill. The thickness is also an essential factor for the design of a ground treatment plan and for the assessment of the seismic behaviour of this material.

The most common methods of determining the thickness of a formation are direct measurement from borehole logs and indirect measurement from the interpretation of geophysical test results.

Borehole logs

The borehole data used in this investigation were obtained from the data records of the Laboratory of Soil Mechanics and Foundations of the Aristotle University of Thessaloniki. These records include more than 400 borehole logs that were drilled at the broader area of Thessaloniki as well as a number of shallow excavations for the investigation of foundations and deeper ones for archaeological purposes. Figure 4 shows the depths of the historical fill from boreholes drilled along the main roads of the centre of the city, the original ground level and the present one.

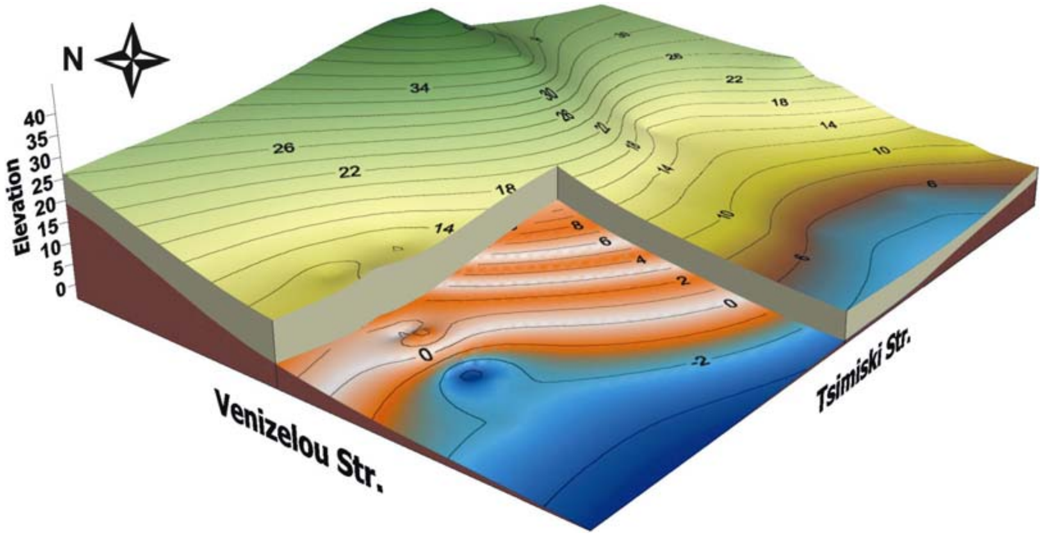

Figure 4. 3-D model of the thickness of Thessaloniki's fill.

The maximum thickness recorded is 12.5 m. It appears that the original ground level of the city presented a steeper topography with long flat areas forming terraces, a pattern that can be very helpful for the further investigation of the thickness of the fill. However, it must be mentioned that profiling fills by borehole data alone is not very accurate and should be further investigated by geophysical methods.

Geophysical methods

As part of the microzoning study of the urban area of the city of Thessaloniki, a large-scale geophysical investigation has been conducted to determine the geometry and the dynamic properties of the surface formations. This geophysical investigation includes, in cases, the application of almost every seismic method. Figure 5 is a map of the isodepths of Thessaloniki's artificial deposits derived from this study. In this geophysical project 14 cross-hole (CH) and 3 down-hole (DH) tests were carried out at locations where other seismic surface methods were inapplicable due to urban restrictions.

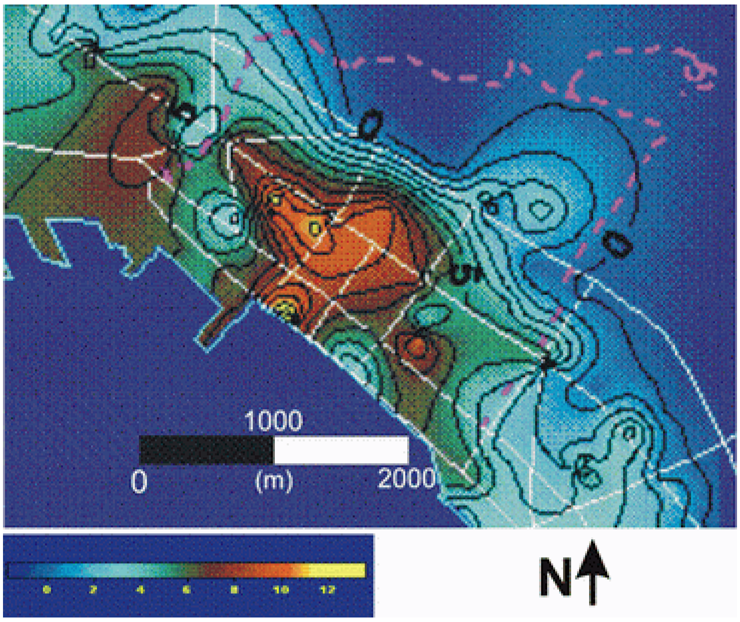

Figure 5. Map of isodepths of Thessaloniki's fill (after Pitilakis et al 1995).

The project was accompanied by all geotechnical data available, comprising 440 boreholes with more than 4,000 soil samples and 171 CPT's, together with the corresponding laboratory tests. All these data led to a preliminary classification and definition of the main soil formations beneath the city (Figure 6), (Anastasiadis et al. 2001).

From the borehole data and the geotechnical zonation the maximum fill thickness that was estimated is 13 m. This is very important for further geophysical investigation because it is the estimate that all future methods are going to be based upon. This layer is also more likely to hold the bulk of archaeological objects, waste, demolition material etc.

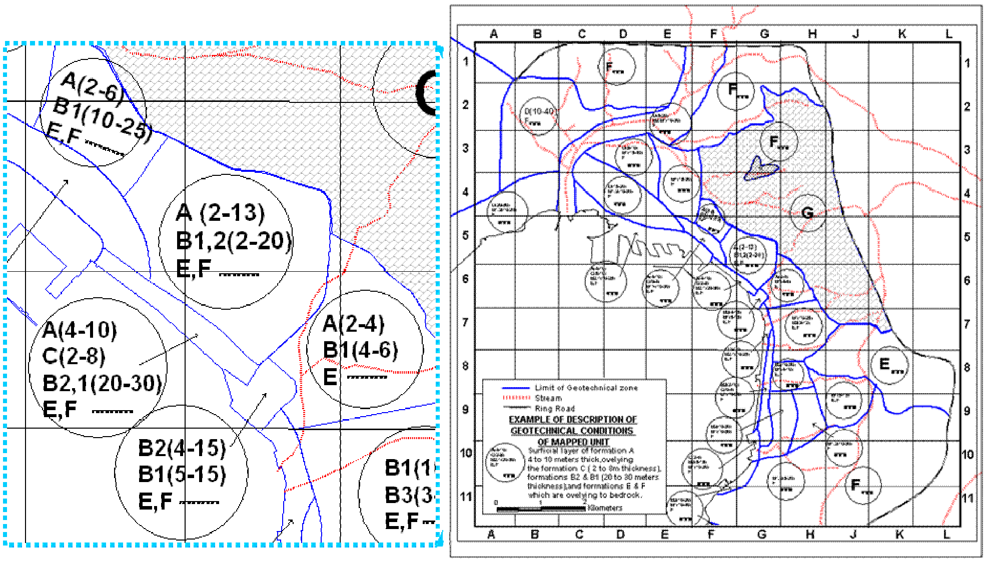

Figure 6. Detailed geotechnical zonation of Thessaloniki based on the physical, mechanical and dynamic properties of the main soil formations (A, B, C, E, F, G). Sequence (in circles) and thickness (parentheses next to soil type) of the main formations (A, B, C, etc) for each geotechnical zone are presented. Shaded area shows the outcrops of the bedrock.
A. Artificial fills of varying origin, mostly demolition material and members of ancient structures, ceramics, etc, with sand and gravels. Covers the historical centre of the city and a part near the coastal line in eastern part of the city and has a thickness ranging from 2 to 13 m.
B1. Surface and coastal river deposits undivided mostly sandy clays to clayey sands with low to medium plasticity with calcareous bodies and rubble. It is very stiff at the centre of the city with thickness ranging from 2 to 10 m.
B2. As B1 but very soft with thickness ranging from 3 to 20 m at the S-E part of the city.
B3. As B1 found having high plasticity and strength characteristics in the eastern part with thickness ranging from 2 to 10 m.
C. Very loose grey to black colour mud and silt with a high percentage of organic material to sandy silts with a very loose structure. Founded along the coastal line lying in the E and F formations.
D. Composed of alluvium deposits, mostly sandy clays to clayey sands with thin layers of silt and sand with high water content, low strength and high compressibility.
E. Very stiff to hard brown-red colour and low to medium plasticity, clay to sandy clay, slight over consolidated with calcareous rubble and thin layers of clay and gravels. Lying over the bedrock and is founded in the centre of the city and eastern part of the city.
F. Very stiff to hard silty-sandy to gravely over consolidated marly clays to marls, with occasional calcareous concretions. Found at the E to EW part of the city.
G. Green schists and gneiss rocks which constitute the basement (after Anastasiadis et al. 2001).

From Figure 4 it is noticeable that the maximum thickness is located at the NW part of the city centre, which agrees in general with the isodepths of Figure 5 (a +10 m zone at the same area). The isodepths show the variation of the thickness clearly enough, but do not include localised excavations, that were probably backfilled afterwards, thus altering the thickness of the fill. An example is shown in Figure 4, where a thickness of about 10-12 m was found in an area that the thickness varies in general between 5 and 8 m.

Therefore the presentation of the thickness of the fill in a contour map cannot be very accurate.

Historical investigation

The estimation of the age of the fill is also an important factor in the implementation of any investigation strategy. The main reason is that time can affect the engineering behaviour of soils by changes in the deposition environment and long-term load effects. If an old fill has already been subjected to many such changes, it becomes more resilient to further changes and, therefore, is less prone to large displacements. According to Schmertmann (1991), who reviewed the mechanical ageing of soils, ageing effects occur in nearly all soil types and can be responsible for large improvements in performance. Charles (1993) suggested that age strengthening is not necessarily associated with chemical bonding or cohesion effects but could often be caused by mechanical processes such as grain slippage and interlocking. Moreover, age can influence other movements related to the placement of a fill such as the long-term settlement under self-weight. This rate is related to the time that has elapsed since fill placement.

The assessment of the age of Thessaloniki's fill can be made from historical investigation, in relation to the time earth fill works took place. Figure 7 is a classification of the fill according to its age. The age of the fill in the area between the natural coastline and the south walls is still in question, the main reason being the insufficient information about the mechanism of deposition. The same figure shows the locations where settlements of buildings have occurred. In the centre of the city all these failures have occurred either in coastal areas that were backfilled or in directions vertical to the coast, following the direction of main roads or old streams. This indicates that the method of placement and compaction was poor which combined with the presence of the layer of organic silt might have adversely affected the mechanical behaviour of the formation.

Figure 7 also shows the locations of possible buried objects and old foundations. The dotted area is the historical centre of the city during Roman and Byzantine times and there is a high probability that the ground in this area is full of archaeological objects and remains not yet excavated. In addition to that, the city had an underground water supply system (operating during sieges etc.); therefore it is almost certain that old reservoirs, small tunnels and other artificial voids might be present in places. The materials present in the fill are mostly rubble from the demolition of old constructions consisting of the building materials of the past (bricks, stones, ceramics, wood etc.). Green schist pebbles and gravels are also present in the fill.

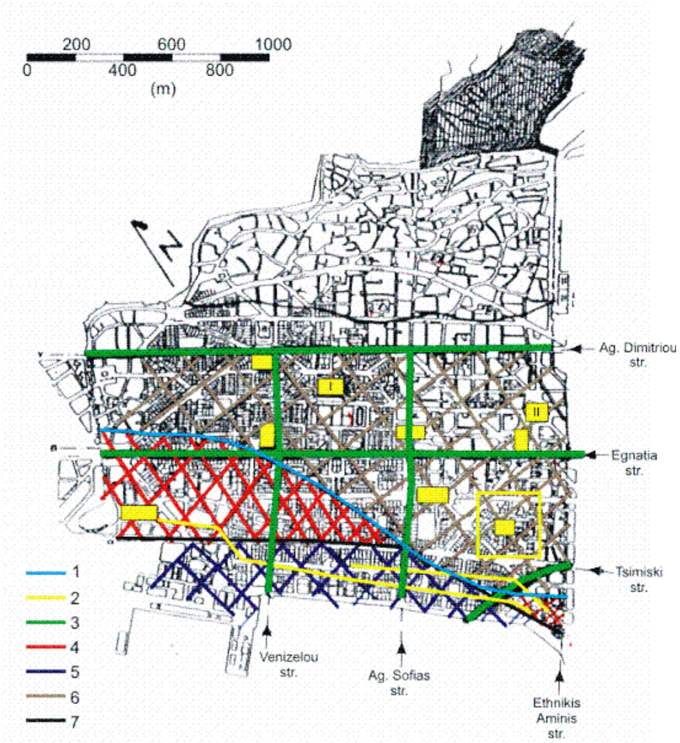

Figure 7. Classification of fill zones according to age. 1. Natural coastline. 2. Historical monuments and remains. 3. Works of urban development 1886-1889 (road construction, backfilling of streams etc.) 4. First expansion of the coast after 1866. 5. Second expansion of the coast after 1900. 6. Historical fill over 1500 years old. 7. First-second expansion boundary. I. Ancient Market II. Rotonda.

Geotechnical aspects

During the recent years a large number of geotechnical investigations have been carried out in the area of Thessaloniki's historical centre in order to assist the design of major constructions and the urban development of the city in general. Therefore, a substantial amount of geotechnical data has been collected, deriving from the application of almost every common method of investigation applied in geotechnical engineering. In the case of Thessaloniki's fill, although in-situ and laboratory testing along with geotechnical zonations can give a quite clear picture of the ground conditions, the geotechnical data cannot be interpreted in terms of providing design values for the full extent of this formation. This is mainly due to the heterogeneity of the fill that is reflected on the extensive range of values of the various geotechnical properties obtained from test results.

The values of geotechnical properties and geotechnical test results presented in this paper are related to the characteristics of the deposits and the nature of materials that have already been analysed. This comparison is necessary to quantify the impact of these characteristics to the engineering behaviour of the deposit. Furthermore, it will facilitate the interpretation of the test results from the geotechnical investigation as well as the design of a more orientated investigation in areas of particular interest. It must be emphasised that the values of the geotechnical properties proposed, are given as an indication of the ground conditions.

Index and classification properties

Classification of the deposit: The fill of Thessaloniki has been described by several researchers. It has been classified as SC-CL 60% and SM, GM, GP according to USCS (United Soil Classification System), (Anastasiadis et al. 2001). It is generally a non-engineered clay fill with sands, gravels, pebbles, rubble, waste and demolition material as well as members of ancient structures, ceramics, wood etc. The thickness of the formation varies from 2 to 13 m and is classified as "medium to deep" fill (Charles 1993).

Particle size distribution: the grain size analyses showed that the fill has the following average values:

1. Percent of soil with particle size less than 0.074mm, $d<0.074mm = 73\pm17\%$.

2. Percent of soil with particle size less than 4.76mm, $d<4.76mm = 40\pm19\%$ (Anastasiadis et al 2001).

The percentage of silt and clay particles is high and the deposits appear to be cohesive. These values refer to the bonding material. The distinction between non-cohesive and cohesive behaviour is a function of other properties in addition to particle size. For example, an uncompacted clay fill composed of lumps of stiff clay may behave more like a non-cohesive fill when loaded, but if inundated it undergoes a collapse compression and, as a result, behaves like a soft saturated clay fill (Charles & Watts 1996).

Density-moisture content: the density or compactness of the fill is a function of the method of placement and the subsequent stress record. The bulk unit weight of the Thesaloniki's fill is approximately 18.5-20 kN/m^3. The table in Figure 8 shows typical field placement densities.

The groundwater level and its fluctuations can have important affects on the engineering behaviour of a fill. These variations cause changes in moisture content, which result the phenomenon of collapse compression (rise of water table) or settlement (lowering of water table). Therefore, the engineering behaviour of a fill should be assessed in respect not only to present groundwater level but also to potential future fluctuations. The mean value of water content ranges between 15% and 25%, although in places it may vary from as low as 9% to as high as 77% (Geognosi S. A.). This value is close to the value of water content of a non-engineered clay fill from the same table. According to that, the porosity of the formation should be no more than 42% and, thus, its void ratio is estimated to range between 0.6-0.75.

		Placement method			Typical field density				
Type*	Fill material	Layer thickness (m)	Number of passes	Roller weight (kN/m)	ρ_d (Mg/m^3)	w (%)	ρ_s (Mg/m^3)	n (%)	V_a (%)
Eng	Clayfill	0.2	6	30	1.68	20	2.65	37	3
Non-eng	Clayfill	–	–	–	1.53	20	2.65	42	12
Eng	Sandfill	0.25	6	30	1.85	6	2.65	30	19
Non-eng	Sandfill	–	–	–	1.55	6	2.65	42	32
Eng	Sandstone rockfill	1.0	4	60	2.03	7	2.65	23	9
Non-eng	Sandstone rockfill	–	–	–	1.60	7	2.65	40	28
Eng	Colliery spoil	0.30	6	40	1.86	11	2.55	27	7
Non-eng	Colliery spoil	–	–	–	1.56	11	2.55	39	22
Eng	Conditioned pfa	0.30	8	40	1.30	25	2.20	41	8
Non-eng	Lagoon pfa	–	–	–	1.17	40	2.20	47	0

Figure 8. Typical field placement densities (after Charles 1993).

Liquidity and plasticity indices: Anastasiadis et al. in 2001 proposed the following mean values:

1. LL = 31±5.5
2. PL = 19±4
3. PI = 12±5.8.

Standard Penetration Test results

A large number of Standard Penetration Tests (SPT) have been carried out in various boreholes in the artificial deposits of Thessaloniki from the Civil Engineering Dept. of AUTH (1985). Figure 9 indicates the distribution and scatter of the results in Thessaloniki's fill, expressed by the number of SPT blows N_{30}. It clearly shows the heterogeneity of this formation in terms of density and strength. N_{30} SPT values are as low as 2 and as high as 60. However, it is interesting that the mean value that derives from the histogram, N_{SPT}=14 is more or less similar to cover strata that exist in many other cities worldwide (Tsotsos et al. 1988). According to this value the deposit can be classified as "medium to dense". Another interesting feature is that the majority of contemporary multi-storey buildings in the city-centre are generally founded on this layer, without presenting significant problems.

The density of the fill is probably due to its age and to mechanical compaction that has been operating through time. The fill has a generally good engineering behaviour but in places its strength becomes very low.

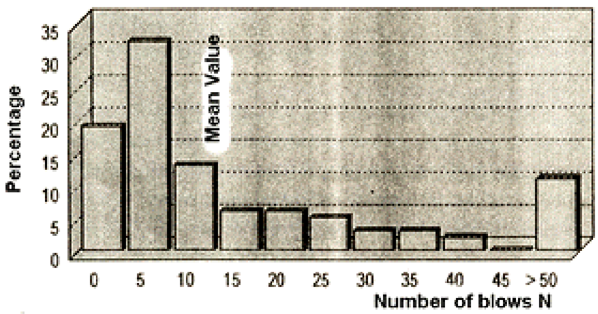

Figure 9. Values of N_{30} SPT test results in Thessaloniki's historical fill (after Tsotsos 1995).

Cross-hole survey

The determination of V_s (shear wave velocity) for the fill of Thessaloniki showed a variation between 100-550 m/s the mean value being 200-250 m/s (Pitilakis 1995). The mean value of the shear wave velocity in the fill is just above 250 m/s. This value is equal to the shear wave velocity in the surface clay formations that cover the city, even outside the city walls. However, there are some variations of that value, especially at the location of the 'Ancient Market' with a rise of the shear wave velocity at 3-5m and 7-9m below ground level (Figure 7). This rise indicates the presence of denser material at these depths that could be either a buried object, i.e. ancient remains, or a concentration of ceramics, wood etc, and transported material (pebbles, gravels, demolition debris).

According to Tsotsos and Pitilakis (1993), the high velocities recorded at Rotonda (Figure 10), at the surface and at various depths, are due to the reception of different types of waves (ground noise, reflected refraction). In the location of the 'Ancient Market' there is a big rise in the velocities underneath the fill, indicating possibly a buried object, since the bedrock at this location is 40-60m deep.

From the V_s values, the shear modulus can be calculated directly. Taking an average value V_s=250 m/s for the fill, it is:

$$G_0 = p * V_s^2$$

where p is the mass density in Mg/m^3. For $\gamma = 20\ kN/m^3$, as it has been estimated, p=2.04 Mg/m^3 and G= 127.5 MPa

It must be mentioned that dynamic moduli are measured in low strain and vary with strain magnitude and time, but it may be possible to relate properties controlling the behaviour of fills under typical monotonic or static loading conditions to dynamic parameters derived from the in-situ measurement of wave velocities.

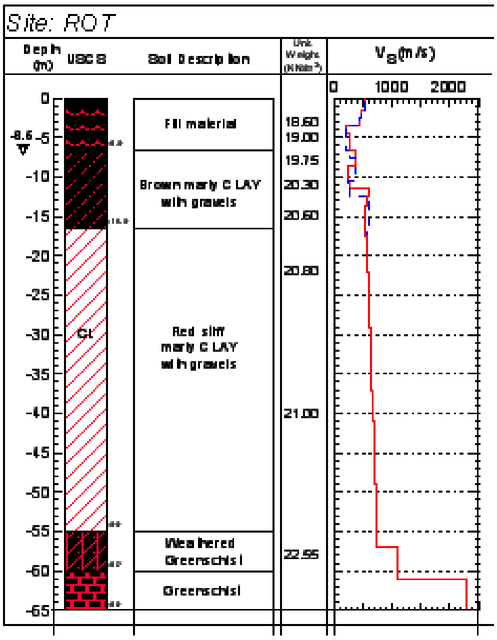

Figure 10. Geotechnical and seismic profile at Rotonda (after Raptakis et al. 1993).

Angle of shearing resistance (φ')

An initial estimation of the angle of shearing resistance can be made from Table 1 according to the material of the fill. For a non-engineered clay fill it varies from 20˚-30˚ and for a non-engineered sand fill from 32˚-37˚. Thessaloniki's fill has been described as a fill with clayey material as connecting soil with sands, gravels and other transported material. It is described somewhere between the above classifications, so an estimation of φ' =30˚-35˚ seems logical, according to the description.

Table 1. Typical values of φ'_{cv} for non-engineered fills (after Charles 1993).

Fill type	**Typical range for φ'_{cv}**
Clay fill	20º to 30º
Sand fill	32º to 37º
Rock fill	35º to 42º

Bearing capacity-vertical stress

In the centre of Thessaloniki there is a small number of historical buildings and monuments that have survived, most of which are Christian churches and fortifications. These buildings are large and their foundations carry large loads. The foundations of almost all the monuments are located in the historical fill of Thessaloniki. Excavations have revealed parts of these foundations and by calculating their size and the load they are subjected to, the vertical stresses applied on the ground were estimated (Tsotsos 1995). The characteristics of the foundations and the applied vertical stress are shown in Table 2.

Table 2. Characteristics of the foundations and applied vertical stress on the foundations of the monuments of Thessaloniki D= depth, B= width, H= height (after Tsotsos 1995).

Monument	Characteristics of foundation	Applied σ_v
Rotonda	D=4.8 m, B=8.6 m, H=3.6 m	360-800 KN/m^2
Acheiropoietos	D=3 m, B=1.4 m, H=2.5 m	250-500 KN/m^2
Agia Sofia	D=4.5 m, B=2.5 m, H=2.5 m	280-500 KN/m^2
Coastal city walls	B=2.85 m	
St. Dimitrios	D=5.7 m, B=1.9 m, H=3.7 m	

The monuments in Table 2 are founded on continuous footings and wooden piles additionally supported the city walls. All monuments have rather excessively loaded foundations and the vertical stress appears to be near the value of the allowed bearing capacity, which has been estimated around 300 kN/m^2, except from the location of Rotonda.

Pressuremeter test results

The pressuremeter test results that are presented are taken from the records of Geognosi S.A. for five representative locations at the centre of Thessaloniki. The tests were carried out with the Menard pressuremeter (MPM). The test results are shown in Figure 11, which is the cross-section along Egnatia Street (Figure 7), for the locations Dimokratias Square, Venizelou str., Agias Sofias str. and Syntrivani square. They are also shown in Table 3.

Table 3. Pressuremeter test results of Thessaloniki's fill.

Location	Depth (m)	E_m (MPa)	Pl (MPa)	E_m/Pl
Dimokratias Square	2.5	5.8	0.75	7.7
	3.5	11.1	0.64	17.3
	5	17.7	1.62	10.92
Venizelou str.	2.5	3.7	0.1	37
	3.5	4.7	0.2	23.5
	5	5.3	0.41	12.9
	6.5	6.6	0.52	12.6
	10	61.2	3.08	19.8
Agias Sofias str.	2.5	6.1	0.1	61
	3.5	7.8	0.28	27.8
	5	3.5	0.2	17.5
	6.5	5.7	0.13	43.8
	8	37.3	1.71	21.8
Syndrivani square	2.5	25.4	0.82	30.97
	3.5	49.3	4.21	11.71
	5	43.9	3.7	11.8

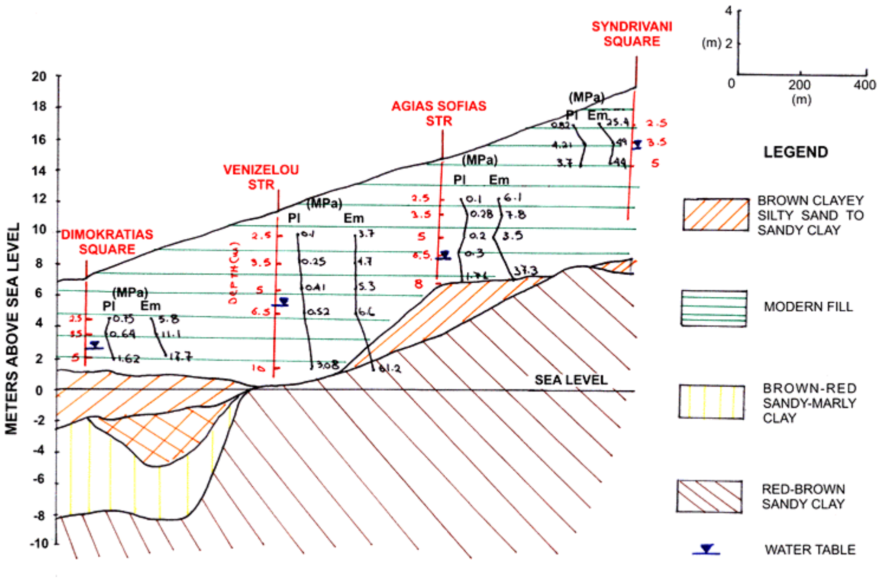

Figure 11. Cross-section along Egnatia str. with pressure-meter test results.

Figure 12 is a classification of soil type based on the ratio E_m/Pl from the MPM test proposed by Clarke in 1995. An observation that can be made is that the ratio E_m/Pl from the results in Thessaloniki's fill is generally bigger than the one for standard soil types in the areas of the old centre of the city (Venizelou str., Agias Sofias str., Syntrivani square), indicating the dominance of debris material at these locations. Another observation is that E_m generally increases with depths with a highest value of 61 in Venizelou str., where the maximum thickness is recorded. Variations occur only in Agias Sofias str., probably due to the big variations in the material and the high probability of buried objects located here, according to the historical review.

Ground type	E_m/p_{lm}
Very loose to loose sand	4–7
Medium dense to dense sand	7–10
Peat	8–10
Soft to firm clay	8–10
Stiff to very stiff clay	10–20
Loess	12–15
Weathered Rock (depends on degree of weathering)	8–40

Figure 12. Classification of soil type based on E_m/Pl (after Clarke 1995).

An interesting comparison would be between the E_m values and the shear modulus G_0, estimated from the cross-hole survey. It is impossible to measure the true maximum shear modulus G_0 from a pressuremeter test because of the lack of sensitivity of the measuring system over the small strain range. In addition to that, G_0 taken from a seismic test produces unacceptably high values of modulus from a pressure-meter curve. On the other hand, Kalteziotis et al, (1990b) undertook MPM tests on a variety of soils in Greece and compared the results with those from cross-hole seismic tests to show that there is a practical correlation between G_0 and E_m:

$$G_0=E_m/2.66$$

where 2.66 derives from the Poisson ratio taken for soils, v = 0.33.

From the results presented in this report, the value of G_0 from the cross-hole tests is one order of magnitude higher than the one derived from the MPM results.

CONCLUSIONS

A thick and heterogeneous layer of artificial deposits covers the biggest part of Thessaloniki's historical centre. This is common in modern cities that have an unremitting urban history. However, the thickness of Thessaloniki's historical fill is much larger compared to other similar formations, varying from 2 to 13m. Therefore, the presence of a formation of this size directly affects the urban development of the city, and its investigation is essential for most of the constructions proposed. This kind of investigation must be based on a strategy applicable to other cases of urban fills as well as a means of ground investigation in cases of extensive urban fills with materials of various nature, origin and geotechnical properties which cannot be categorically implemented on the basis of design parameters. This strategy should take into account the nature of materials present, their origin, their method of deposition and/or placement and the age and thickness of the formation.

The strategy of the investigation proposed aims to classify the fill based on the above physical properties and factors relating to the history of the fill. This classification could assist in the recognition of similar types of ground engineering behaviour and the assemblage of situations of similar potential hazards. The final classification will be carried out based on conclusions derived from desk and field study on the geological and historical review along with the geotechnical data available, which can be related to these conclusions.

Thessaloniki's fill consists of material of varying origin due to the continuous land use of the area for more than 2,000 years, its geomorphological profile, the geographical setting of the city and the seismogenic character of the region which produced destructive earthquakes. The geotechnical parameters and test results that are presented show the heterogeneity of the formation under investigation. The main difficulty is to determine the index and classification properties of the fill, which can be compared to the results of the geotechnical investigation. Therefore, the only comparison that can be made is between the results of different tests. This poses a lot of problems because the results of most field-testing techniques cannot be compared due to their different method of execution. If we take as an example the pressuremeter test and the cross-hole survey results, there is no reason why pressuremeter test results should be similar to those of the geophysical method. The rate of loading, the stress path followed during installation and testing and the drainage conditions are different.

It is important that an engineering geology study adopts a multi-disciplinary approach to the design and interpretation of an investigation of man-made ground. It is necessary to use and combine all information and investigation methods available to assess the characteristics of an urban fill. The results of the investigation should not be seen in isolation, but should compound and add to one another. A general investigation to assess the suitability of a fill for development should include: Study of the history of the site, field study and ground investigation, in-situ and laboratory tests, load tests and geophysical tests.

Corresponding author: Mr Nikolaos Chatzigogos, Aristotle University of Thessaloniki, Geology, Alexandreias 60, Thessaloniki, Macedonia, Greece. Tel: +30 2310886925. Email: chatzi5@hotmail.com

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