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GEOTECHNICAL CHARACTERISTICS OF OUTCROPPING DEPOSITS IN THE SIBARI PLAIN

CARACTERISTIQUES GEOTECHNIQUES DES DEPOTS AFFLEURANTS DANS LA PLAINE SIBARI

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SYNOPSIS: The Archeological site of Sibari, located at the northern end of Calabria (Italy), has been affected since the ancient time by a complex and wide subsidence. Three levels, dated from VI century B.C. to I century B.C. have been discovered between 3.50 and 7.00 m below today's field level. The studies carried out allow us to suppose the possible causes responsible for the phenomenon. They can be ascribed to neotectonics, glacioeustatic changes of the sea level, primary and secondary consolidation and reduced pore pressure resulting from underground water withdrawals. A large number of boreholes has been sunk and a piezocone test was carried out in a tooled one. A first classification of soils has been made by up to date classification paper and by laboratory test results.

1. FOREWORD

Archeological excavation at several sites in the Plain of Sibari has provided irrefutable evidence of an important soil subsidence phenomenon which has certainly continued to evolve until these days since the earliest historically recognized settlements.The constituent elements of the subsidence process were investigated in a first series of interdisciplinary surveys, in an attempt to understand the nature of the phenomena that reflect the most conspicuous underlying causes. This paper describes the features of the sites with respect to structural geology, stratigraphic characters, glacioeustatic events, hydrogeology and technical behaviour of soils in the plain since all these factors contribute, to some extent, to the still ongoing slow susidence process. The attempt to integrate this body of information into an organic frame, while not fully exhaustive,is, if anything, instrumental in providing guidelines for surveys based on a much wider and well-founded knowledge than was hitherto available in connection with the area.

Our investigations showed evidence that the causes of subsidence can be ascribed essentially to four concomitant circumstances:
- neotectonics
- glacioeustatic changes of sea level
- primary and secondary consolidation of recent sediments
- reduced pore pressure resulting from underground water withdrawals.

2. THE ARCHEOLOGICAL SITE

Several archeological seasons carried out since 1879 with the aim to locate ancient Sybaris,yielded evidence of three superimposed levels of settlements, indicating continuing life between the VI and the last I century B.C.: the three levels are located between 7 and 3.5 m below today's field level (Fig. 1). The most extensive finds are concentrated in two areas, Parco del Cavallo and Stombi, extending between what was identified as the former beds of the Crati and Coscile rivers, now flowing as a single mouth into the Jonian Sea. Moreover, historical, archeological and aerial photogrammetric evidence indicate that the ancient city bordered the sea close to the present confluence of the two rivers and that their common delta has since then progressed by about two Km toward the Jonian Sea.

3. GEOMORPHOLOGY

Sybaris archeological site is located at the northern end of Calabria region, lying in an alluvial plain with the lower valley of the Crati river and its tributaries running across it. To the North, the plain is in contact with the mesozoic calcareous dolomitic massifs of Mount Pollino, to the South it borders the Sila crystalline massifs.

The site is a depression trending approximately ENE-WSW. The upper part of the basin is filled by an alluvial plain whose depth increases, as one proceeds from N to SE, from 103 m to 478 m south of the Crati river; measurements were taken from a large number of boreholes sunk on behalf of the Italian National Research Council (C.N.R.) for this particular study, and especially by deep drilling in the 1950's to detect presence of hydrocarbon-bearing strata. (Fig. 2).

The area where the Crati and Coscile rivers flow into each other is scattered with marine and fluvial terraces consisting of coarse sand, with polygenetic gravel lenses. The terraces are very likely to be associated with uplift phases that occurred between the

Pliocene and the Pleistocene.

The sediments making up the plain are alluvia consisting of alternations of sands, clayey sands, silty clays and gravels. At various depth, peat level intercalations are encountered.

4. TECTONIC SETUP

The Sybaris plain forms a graben enclosed by several differently oriented fault systems: the most important one, trending NE-SW, is represented by Sangineto line that separates it from the Pollino massifs (Amodio Morelli et al., 1976). Another fault zone encloses the plain from the South along the Jonian coast of Sila. The Sangineto line, which was interpreted as a left strike-slip fault, played an extremely important role: in fact, the subsiding effect of the plain, is due to the disjiunctive tectonic phase which has been affecting the entire Calabrian arc since the Tortonian to date and is characterized by the opening up of subsiding trenches gradually filled with more and more recent sediments (Ghisetti and Vezzani, 1981).

The Pleistocenic and recent activity of the above described fault systems can be summed up (Fig. 3) by distinguishing steadily, or predominantly, uplifting zones since the Pliocene, and zones showing complex movements and subject today to downwarping and/or uplifting (Tortorici, 1983).

More precisely, areas characterized by downwarping, like the Sibari plain, in fact show a tendency to uplift at much lower rates than the surrounding areas that some workers believe to be lifting up to 3 mm/year: however, this data cannot be objectively confirmed since it would be hard to quantify the amount of tectonic uplifting and/or downwarping due to lack of precise geodetic measurements.

Instead, the easternmost portion of the Sibari plain did subside during the Holocene as a result of tilting with an axis taking roughly the N-S direction.

5. GLACIOEUSTATIC CHANGES OF THE SEA LEVEL

The coastline trend along the Jonian arc has undergone considerable changes during the Quaternary (Cotecchia and Magri, 1967 ; Cotecchia et al.1969).The end of the Thyrrenian was characterized by a regression which lowered the sea level to about 100 m below today's level to roughly correspond to the current 100 m depth contour. Such a conspicuous and sudden drop of the sea level brought about the beginning of a very intensive regressive erosion phase, due to remarkable depression of the surface drainage system all around the Ionian coast.

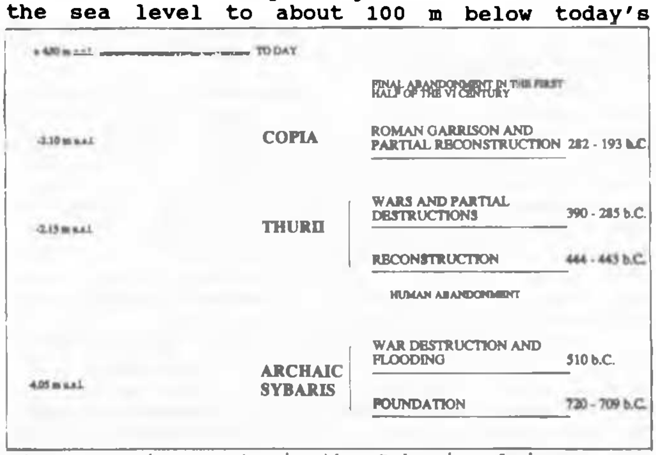

Fig.1 - Main events in the Sybaris plain

Subsequently an equally quick transgression again raised the sea level about 6000 years ago almost to its present value. Later on, mean sea level continued to rise, with minor fluctuations during the last millennia, until the present state was reached.

Finding peat strata led to very important conclusions in connection with these phenomena. The thickest peat layers were found in a borehole at Stombi, where three levels, found respectively at 8.50-9.00 m, 41.00-44.00 m and 60.80-61.00 m below field level, made it possible to use radioactive carbon dating.

Absolute age with respect to the present (1950 was taken as the reference year) were found to be 4685±69 at the shallowest level, 8410± 90 at the intermediate level and 9895±142 at the deepest level (Fig. 4).

Absolute ages correspond to the post-glacial Holocene. More precisely, the deepest level can be ascribed to the Preboreal period and the most superficial one to the Atlantic-Subboreal, pratically marking the transition from the Mesolithic to the Neolithic when the whole area was involved in the Flandrian transgression.

Bearing in mind that peats are the product of sedimentation in a transitional environment of a swampy type, we may assume that they were formed at sea level: from the diagram in the figure showing glacioeustatic changes of the sea level, we may infer that, at the time when

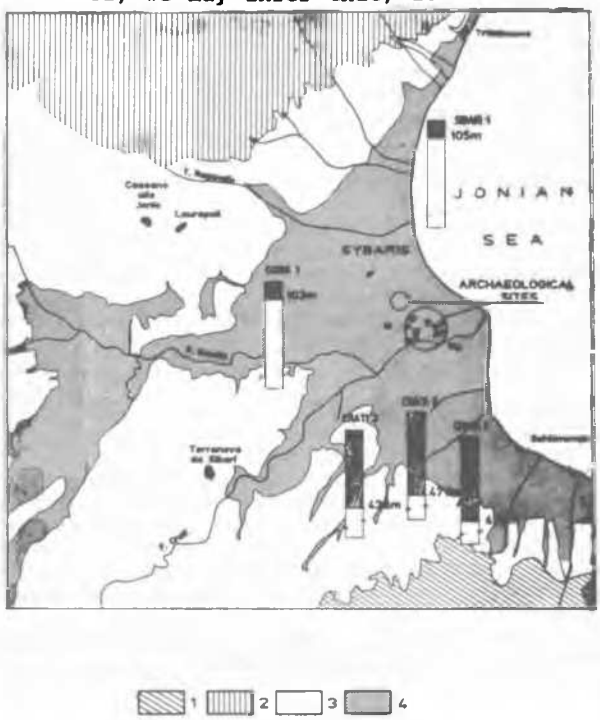

Fig.2 - Thickness of alluvial deposits established by deep boreholes sunk in the Sybaris plain: 1) Crystalline rocks. Paleozoic-Mesozoic; 2) Carbonate rocks. Mesozoic; 3) Plio-pleistocenic sediments; 4) Alluvial sediments. Holocene.

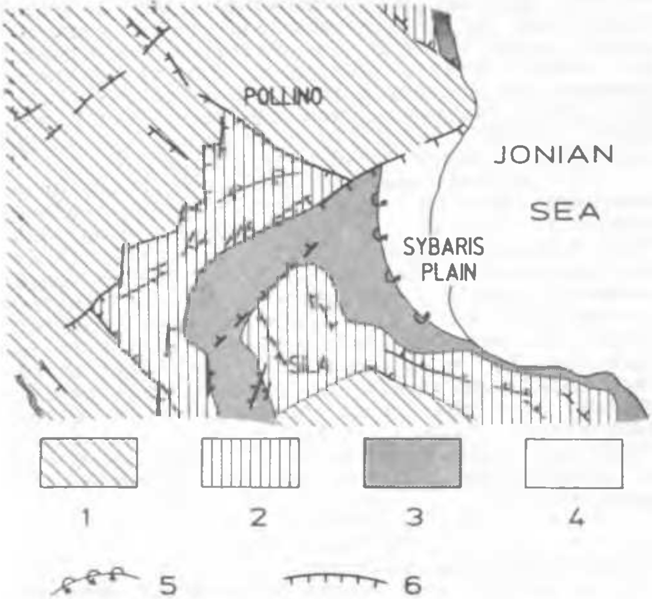

Fig.3- A synthesis of the neotectonic map: 1) prevaingly uplifting areas; 2) subsiding areas followed by uplift; 3) areas showing complex movements followed by uplift; 4) areas showing complex movements followed by downwarping; 5) tilt axes; 6) faults.

the three horizons were deposited, the sea level was lower than it is now by about 5 m, 20 m and 37 m respectively.

One can then conclude that, since the deepest peat level now lies at 60.80-61.00 below field level, its absolute settlement since deposition was about 24 m, with a subsidence rate (the tectonic and the geotechnical component taken together) of about 2.4 mm/year, while the average annual settlement in the upper levels was lower. Instead, the total rate of subsidence, including apparent subsidence due to glacioeustatism, shows values of 6.1 mm/yr and 2 mm/yr. In a previous study (Guerricchio and Melidoro, 1975), subsidence rate was estimated at 4.3 mm/yr. This indicates a slower subsidence rate in the upper part of the plain.

Our findings also show that deposition of the last alluvial sediments was especially fast between 9000 and 4000 years ago (8.5 mm/yr) whereas later on the rate of deposition in terms of sediment thickness was much slower (2 mm/yr).

6. HYDROGEOLOGY

Deep boreholes sunk at the Writers' request contributed to shed more light also on problems of hydrogeology. Special boreholes were used to place 2 electropneumatic piezometers in gravelly strata and a Casagrande piezometer designed to measure the superficial groundwater. The coefficients of permeability which can be derived in situ pseudoquantitatively by means of dissipation tests carried out with the piezocone (to be discussed in detail further down in this

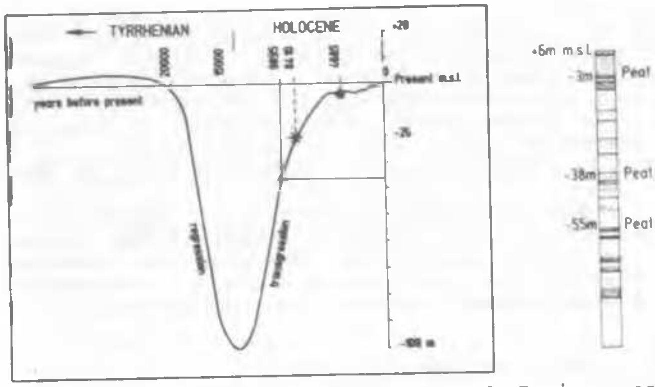

Fig.4 - Glacioeustatic changes of Jonian sea level and the three peat horizons found in the Stombi borehole. The three peat levels were radiocarbon dated; at present they occur at -3 m, -38 m, and -55 m below m.s.l..

paper), range from a maximum value of about 10^{-3} cm/sec to a minimum of about 10^{-7} cm/sec. Consequently, the variability of hydraulic conductivity from one stratum to the next was found to be quite important.

The potentially very rich superficial groundwater running very close to the archeological finds can be encountered at 0.50 m below field level: it is barred seawards by the seawater intrusion wedge and is currently drained by a system of well-points at around Parco del Cavallo more or less down to 0 level, but does not let in brackish water intrusion although it is the same of mean sea level.

Water extracted from excavations is comparatively salt-free, its salt content being 0.6 g/l while chlorine content is extremely low. Measurements taken in the two electropneumatic piezometers in summer 1992 made it possible to identify the presence of two more confined aquifers at about 50.00 and 70.00 m below field level.

Drinking and irrigation water for the plain is pumped from these deeper aquifers. Presence of sulfurized hydrogen and methane was observed in boreholes drilled since the 1950's: in fact it is indicative of reactions and reduction phenomena between existing organic matter and fossile saline water confined in the deeper strata that are believed not to be naturally recharged and that, if extracted, could be the starting cause for accelerated subsidence. By making reference to the trigonometrical levelling plot drawn between the sea and the excavation site, it was found that the IGM datum point marked on the Crati river bridge in the 1971 has since then sunk by at least 20 cm in absolute terms. All the above mentioned data, however, require verification within the framework of more extensive checking programs.

7. GENERAL GEOTECHNICAL CHARACTERISTICS

Some undisturbed cores taken from borehole n.1, deliberately located close to the one with the piezocone, were used for classification tests in the laboratory. Geotechnical data on soils in the Plain were not known except for those reported in a work by Kerisel and Matteotti (1975) describing similar soils from area located slightly more to the south (Port

of Sibari). A synthesis of our findings is given in figure 5. It is clearly seen that all the investigated soils have a rather varied grain size distribution, ranging from silty clays and silts with significant percentages of clays and/or sands, to sands.(Fig. 5) Plastic properties show a similar variability:
WL min = 30%, WL max = 58%, PI min =10%, PI max = 38%.

Natural unit weights are rather low, around 16.0-17.0 KN/cu.m. These latter values will prove useful to interpret the results obtained from the piezocone for our evaluation of underdrained strength and compressibility.

8. RESULTS OF PIEZOCONE TESTS

As mentioned earlier on, a continuous piezocone test was carried out at Stombi down to a depth of approx. 100 m. (Fig.6)

Selecting the instrument on which we could rely for detailed information on the soils forming the Crati river alluvial plain was conditioned by several factors, (Baldi et al.,1986):

- the possibility to get the most continuous obtainable measurements;
- the possibility to measure hydraulic parameters along with the mechanical parameters of sediments;
- the possibility of using classification systems capable to offer a sufficiently reliable reference frame.

The test enabled us to evaluate changing soil strengths around the cone tip and excess pore pressures with increasing depth. Test diagrams are shown in the figures. Note that in a first portion extending from approximately 44 to 50 m and down a short tract just before the 70 m depth we had to send down a casing as we were proceeding through coarse materials (gravel and pebbles).

A first analysis shows that the sections passing through rather fine-grained, and thus compressible, materials are essentially located at varying depths between 22 and 43 m.

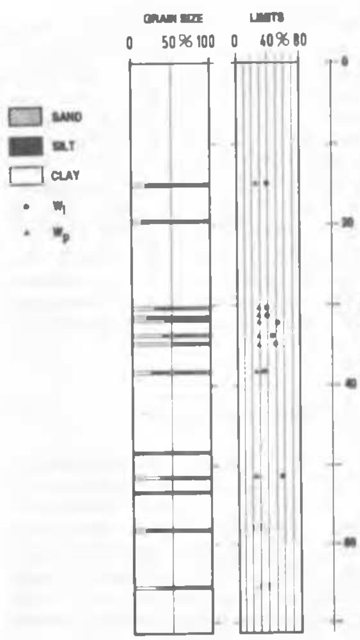

Fig.5 -Grain size distribution and plastic properties of some sample cores taken at different depths.

Thinner levels are present at greater depths. By way of indication, the overall percentage of fine materials (clays and/or sands) occurring down the entire explored depth is about 40-45%. Estimates of this kind, however, are a complicated procedure given the fact that (Atkinsons and Sallfors, 1991) the soil volume actually involved in the measurement cannot be clearly defined.

It is furthermore a known fact that data obtained from a penetrometer test, unless properly dealt with, may highlight "disturbances" capable of disguising the trends and indications that a test of this kind would normally yield. Therefore, data filtering procedures were used although they are not described here for lack of space. Still, it is possible to work out a classification of penetrated materials by means of special charts. In the chart used in this study (Robertson, 1990), (Fig.7) tip resistance corrected (qt) and normalized, i.e. $(q_t - \sigma_{vo})/\sigma'_{vo}$ is plotted as ordinate and the parameter Bq equal to

$$B_q = \frac{\Delta u}{q_t - \sigma_{vo}}$$

is plotted in the abscissa.

A fairly thick cloud of dots is observed in zone 3 identifying clayey soils and silt clays, especially where the Bq ratio is in the order of 0.6-0.8, indicating essentially normally consolidated soils. Moderate crowding of dots is also observed in zones 4-5-6 corresponding to soils with a grain size

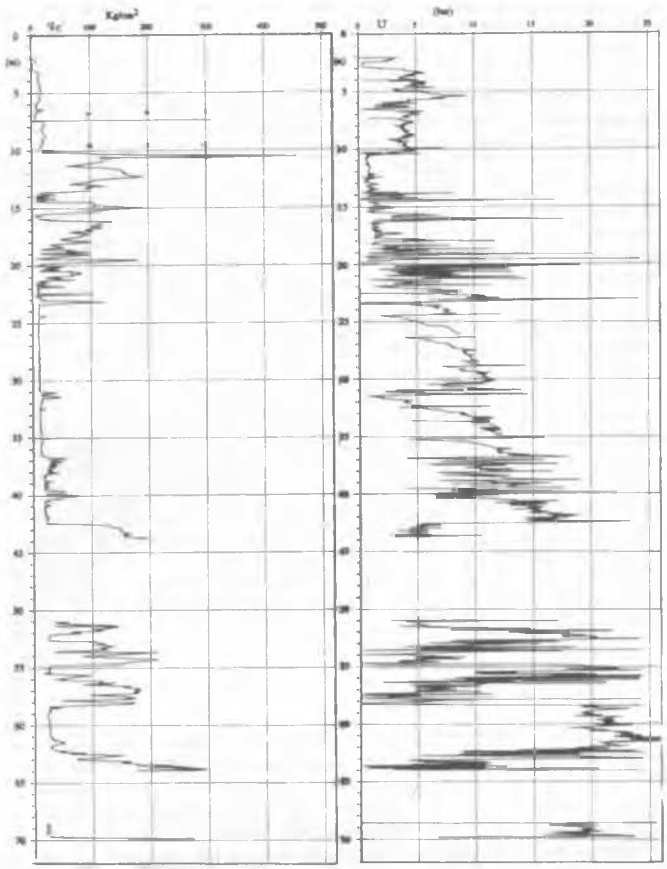

Fig. 6a - Soil strength around the piezocone tip with changing depth.

Fig. 6b - Excess pore pressure (U) measured with the piezocone at different depths.

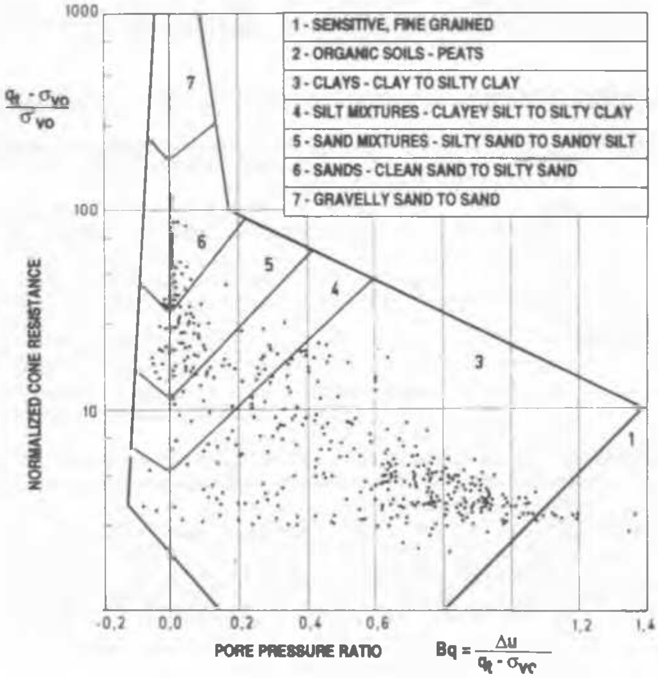

Fig.7 - Robertson's classification chart.

distribution ranging from clay silts to sands, especially in those zones where Bq is rather close to zero.

The great scatter of points is certainly related to the peculiar nature of the deposition, with a not quite negligible contribution from several factors variously affecting the results of the test in various degrees.

Between 22 and 43 m, where a significantly larger mass of soft clayey and/or clay-silty material was identified, undrained shear strength Su was equally evaluated from the data provided by the piezocone.

We know that (Baligh,1975) Su can be estimated by applying the following relation:

$$S_u = \frac{q_c - \sigma_{vo}}{N_k}$$

where Nk =15 + 3 where σ_{vo} is total pressure at the site and qc is the tip resistance.

The latter factor (Nk) is greater, the higher the rigidity index IR considered as the ratio between the undrained shear modulus G and the relative shear strength Su, namely:
IR = G/Su

σ_{vo} can be indifferently evaluated either as total vertical stress at the site, or as total horizontal stress at the site, or still as octahedral stress. In our case Nk was assumed to be equal to 15 in the average and σ_{vo} to be equal to total vertical stress.

The results obtained by applying the above formula indicate a clearcut increment of Su with effective stress: this confirms that we are dealing here essentially with materials that are certainly not overconsolidated. A UU test carried out on clay core taken at a depth of about 30 m showed a Su value of 40 KPa, in excellent agreement with the value derived by processing the piezocone results. It may be of some interest to compare Su as calculated above and the one that can be evaluated, by means of empirical relations, on the basis of the plasticity index and liquid limit.

Such relations are applied having in mind the minimal and maximum values found in connection with PI and WL indexes.

It is here worth mentioning that the previously mentioned work by Kerisel and Matteotti confirmed the applicability of Skempton's well-known expression (1957) for NC clays which relates undrained strength Su, effective stress and the plasticity index, i.e. (for PI = 20 and σ'_{vo} = 0.77h)

$$S_u / \sigma'_{vo} = 0.18\ h$$

The data were also verified against the relations of Bjerrum and Simons (1960) and Karlsson and Viberg (1971).

Su / σ'_{vo} = 0.45 (PI) PI 5%
= 0.005 (WL) WL 20%

By assuming the already mentioned maximum and minimum values of the plastic properties, the above relations give:

Su / σ'_{vo} min = 0.14
max = 0.29

These values compare well with the Su trend resulting from the piezocone test, given the fact that the latter evaluation shows values similar to, or just slightly higher than, those found by Kerisel and Matteotti. Note that the Su / σ'_{vo} ratios are between 0.15 and 0.40 for other Italian soft soils and are therefore in good agreement with the fine soft soils in the Sibari plain.

Some dissipation tests performed while the piezocone trial was in progress, also made it possible to check the permeability of the penetrated materials.

Following the indications by Larsson and Mulabdic (1991), we are presenting here table 8, which shows remaining excess pore pressures observed, in relation to depth, 5 and 10 minutes after the beginning of the dissipation test.

Soil exhibiting Remaining Excess Pore Pressure values lower than 0.2 (after 5 and/or 10 min) are considered to be free-draining. Semi-draining soils are soils that show values between 0.2 and 0.4 after 10 minutes and between 0.2 and 0.6 after 5 minutes. The third range or R.E.P.P. with values up to 1 applies to soils defined as not draining. The results shown in the Table simply confirm the above reported data and clearly show that the variability of the characters, grain size

REMAINING EXCESS PORE PRESSURE		
	AFTER	
DEPTH	5 min	10 min
4.00 m	0.52	0.63
7.90	0.54	0.65
10.25	0.08	0.03
16.10	≃0	0
22.60	[illegible]	0.61
30.00	0.32	0.20
30.70	0.73	0.66
39.50	0.04	0.03
53.63	0.04	0.03
57.60	0.10	0.08
60.91	0.03	0.02

Fig. 8 - Piezocone dissipation tests of pore overpressures at different depths: Remaining Excess Pore Pressure after 5 and 10 minutes.

distribution and plasticity, are also reflected in the permeability characters.

9. CONCLUSIVE REMARKS

Herodotus (484-425 B.C.) relates that the Crotoniates, the Sybarites' chief rivals, defeated them in 510 B.C.: before razing the archaic city of Sybaris, they deviated the course of the Sybaris river (now called Coscile) so that the whole city was submerged. It is very likely that this circumstances had been made possible by one of the strong floods that, with heavy masses of transported material, had again and again devastated the Sybaris plain and thus deviated the area's stream system from its course. This resulted into an exceptionally fast accumulation of those sediments that are still subject to the gravitational settling phenomena we have discussed at the beginning of this paper.

A history of marked neotectonics eventually led to a morphology characterized by strong relief energies. Together with the primary and secondary consolidation phases of the fine fraction in the deposits that accumulated gradually before and after the foundation of the Achean colony, this process contributed to the unrelenting soil subsidence, hence to the present position of the ancient settlement levels now lying several meters below sea level.

Also the southward deviation of the Sybaris river, reported by Herodotus, can somehow be explained by the natural causes which are at the origin of the Coscile river flowing into the Crati river, the two rivers that had well-differentiated mouths and deltas flowing into the Jonian sea while archaic Sybaris was standing. Since then, the Crati river mouth moved eastward by about 2 Km from the coastal stretch which the city of Sybaris overlooked in the 6th century B.C..

The stratigraphic and geotechnical analysis of the quaternary alluvial deposition strata, specifically drilled for this research down to a depth of over 100 m, the rapid development of established sedimentation processes, and the normally consolidated - if not underconsolidated state- of the fine materials occurring down to a very great depth justify the still ongoing natural subsidence which was the real cause why the archaic city eventually disappeared.

In addition, a local accelerated subsidence could be demonstrated. While still limited to a few dozen centimeters, it has certainly been caused by man through the withdrawal of water from deep aquifers during the last twenty years.

Research work is to be continued along the following lines: in addition to the geotechnical analysis of clay-silt core samples to be extracted from new boreholes, accurate and advanced geodetic measurements have been planned for which G.P.S. (Global Positioning System) stations will be positioned along lines running from the relief flanking the graben in the Crati river valley down to the archeological area and to the present coastline. By so checking the entire area, it will become possible to quantitate the different components (neotectonics, "slow" geotechnics, accelerated geotechnics through man-made derangement of groundwater, glacioeustatic changes of sea level) of the subsidence now occurring in the plain.

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