

CHARACTERIZATION AND DATATION OF HOLOCENE MUD LAYERS FROM THE SUBSOIL OF THE URBAN AREA OF AVEIRO (PORTUGAL)

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Abstract. The present paper intends to be a contribution for a better understanding of some relevant geologic and geotechnic features of the urban area of the town of Aveiro. An attempt was made in order to correlate the geotechnical properties with the mineralogical and textural parameters of the terrains that in the urban area of Aveiro consist mainly of weakly consolidated sands, clays and muds of Holocene age. The analysed geotechnical parameters point out that the Holocene muds are less expansive and plastic than the Cretaceous clays and marls. The later are richer in clay particles whereas muds are richer in silt particles. The mineral assemblages express lagoonal environments, under depositional conditions characterized by an irregular detrital supply, in a confined, with low salinity, littoral area. The first geochronological results obtained from the analysis carried out by the «Instituto Tecnológico Nuclear» (Lisboa), utilising the radiocarbon method applied to bivalve shells found out in interbedded mud layers, provided ages placed in the range 1960 ± 90 and 6450 ± 140 years BP.

Key Words: Holocene, muds, clays, radiocarbon data, Aveiro, Portugal.

Resumen: El presente trabajo pretende contribuir al mejor conocimiento geológico de los materiales del área urbana de la ciudad de Aveiro. Se trata de un intento de correlacionar las propiedades geotécnicas con los parámetros correspondientes a la composición y textura de los materiales, que en el área urbana de Aveiro están constituidos principalmente por arenas no consolidadas, arcillas y lodos. Los parámetros geotécnicos analizados indican que los lodos holocenos son menos expansivos y menos plásticos que las arcillas y margas del Cretácico. Estas últimas contienen más partículas de arcilla mientras que los lodos son más ricos en limo. Las asociaciones mineralógicas indican un ambiente de lagoon, en que las condiciones de sedimentación estarían caracterizadas por un aporte detrítico irregular en un litoral, confinado, de baja salinidad. Se presentan nuevos datos geocronológicos referentes a diversos niveles de lodos recientemente descubiertos en el área urbana vecina del Canal Central de Aveiro.

Palabras clave: Holoceno, lodos, arcillas, datación por ^{14}C , Aveiro, Portugal

1. Introduction

In geological terms, the Aveiro region corresponds to the northern sector of the Portuguese Occidental Meso-Cenozoic sedimentary basin (Figure 1). Muds and clays are quite common in the Aveiro region, and

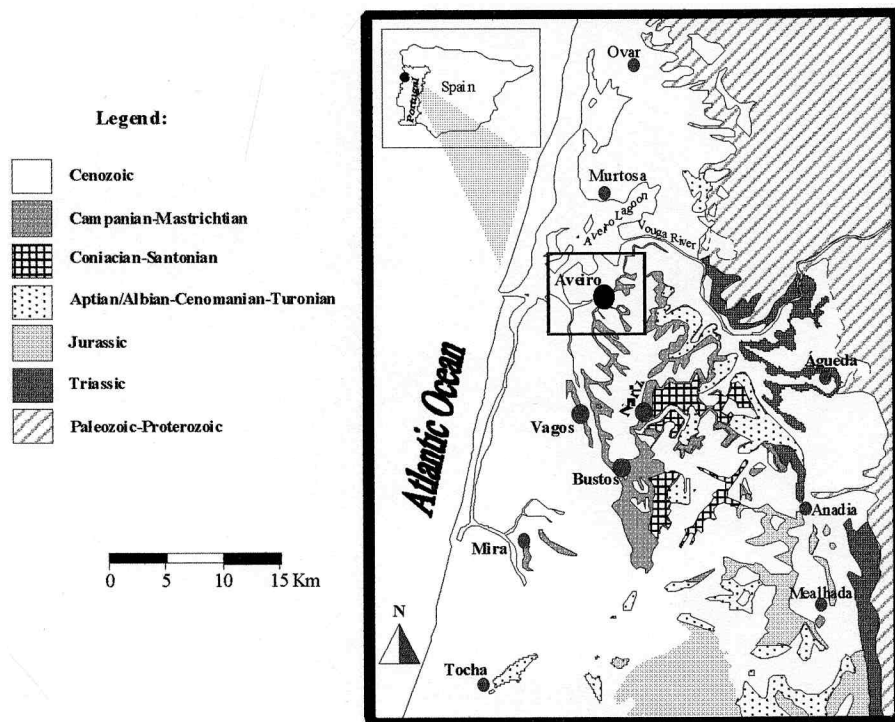


Figure 1. Location and Geological setting
Localización y marco geológico

can be found in outcrops or lying immediately underneath the ground surface. In this paper, the terms mud and clay have the meaning referred to in Weaver (1989). These materials have been the subject of research since many major civil construction works have to be founded in such unconsolidated or weakly consolidated sedimentary rocks dated from the Holocene and Upper Cretaceous, respectively (Barbosa, 1981; Rocha, 1993; Rocha & Gomes, 1993/4; Teixeira & Zbyszewski, 1976).

Besides the determination of some relevant geotechnical properties such as: expandability, plasticity and rheology, an attempt was made in order to correlate the results of these properties with both the composition and texture of muds and clays.

At the present is under construction right in the center of the town an urbanistic complex, called «Forum de Aveiro», whose building foundations attained 10 meters underneath the topographic surface. The «Forum de Aveiro» as a civil construction is very interesting as regards to both its huge dimensions and to the site of its location. In fact, the construction area is critical in geologic terms due to its location along the left margin of the «Canal Central». Layers of sand and muddy sands do occur making difficult the choice of the most convenient position for building foundations. On the other hand, a different sort of problems have to be dealt with due to water infiltrations and instability of the excavated ground. Therefore, the geotechnical works being carried out were used as a convenient basis to fulfil the main goal of the planned research. Figure 2 shows a sketch exhibiting boreholes location and the lithologies found in each borehole.

2. Geologic setting

In geomorphologic terms, the urban and suburban areas of Aveiro are characterized by extensive plains, the most part of them being occupied by Quaternary marine deposits; the littoral plain is covered by dunar deposits.

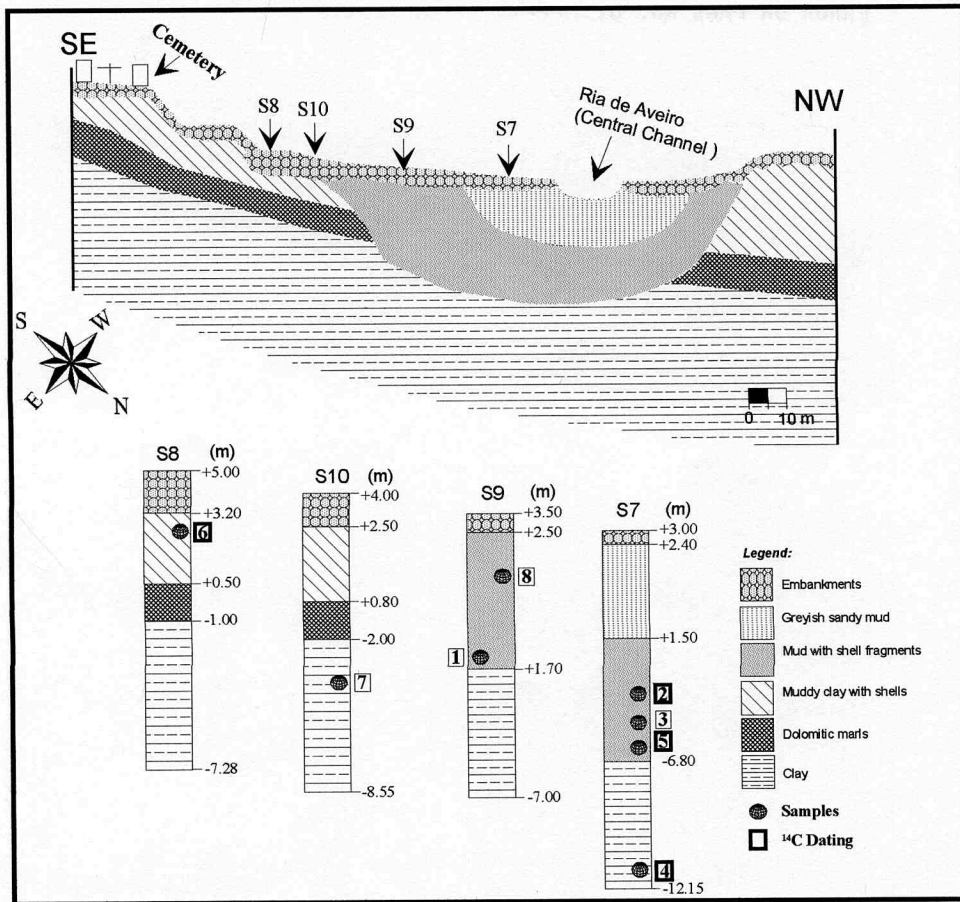


Figure 2. Schematic cross-section of the area under study showing the boreholes location and lithologies
Sección esquemática del área en estudio mostrando la localización de los sondeos y las diferentes litologías

At the Aveiro region a gap in the stratigraphic record do occur beyond upper Cretaceous. In fact, Paleocene, Eocene, Oligocene and Miocene formations have not been identified in the region so far. Nevertheless, in the marine continental shelf just in front of the present shoreline, Paleogene and Neogene deposits overlies Maastrichtian deposits displaying an overall thickness estimated at about 550 meters. In post Cretaceous times, the region under study was immersed by the waters of a shallow sea in which Plio-Pleistocene and Holocene sediments were deposited. Pliocene and Pleistocene outcrops do occur corresponding mainly to old beach deposits and to fluvial terraces.

In the Aveiro region the Quaternary sediments are well represented in terms of outcrops, extension and thickness. The study of these sediments can provide interesting information about the morphological evolution that did take place in recent times. The main Quaternary formations in the Aveiro region consist of deposits attributed to old beaches and fluvial terraces of Plio-Pleistocene age as well as of alluvial and lagoonal Holocene deposits; in both cases, these deposits are partially covered by recent dunal deposits and recent sediments of the Aveiro lagoon.

In the littoral to the north of Aveiro, coastal erosion exposed the so-called Praia de Cortegaça Formation (Granja & Carvalho, 1991, 1994), consisting of, from the base to the top, of: greenish fine silty-clayey sand overlaid by sandy unit exhibiting cross-bedding. Coal fragments incorporated in the greenish fine silty-clayey sand allowed a radiocarbon datation with values in the range 6850 ± 60 to 5500 ± 160 years BP. Overlying the sandy unit lies a podzol exhibiting bioturbated horizons. Datation carried out on coal fragments incorporated in the podzol provided values in the range 3490 ± 60 to 950 ± 80 years BP. Finally, at the top of cross-sections of the studied outcrops lie bioturbated beach and dune sands.

The Aveiro lagoon (Ria de Aveiro) is a barrier type lagoon. Its formation started less than 1,000 years ago when a sandy spit developed and proceeded southwards isolating the river Vouga estuary from the Atlantic Ocean.

Particular attention was deserved to the alluvial formations that form the lagoon substractum. Having in mind the availability of data that could allow a better understanding of the morphoclimatic evolution of the region, sedimentological, mineralogical and geochemical studies have been carried out both in the surficial and subsurficial lagoon sediments. Sampling for these studies, that paid particular attention to the clay fractions, was carried out either on samples derived from boreholes or collected on the surficial sediments.

The studies referred to allowed the subdivision of the Quaternary alluvial sediments in informal units (Rocha & Gomes, 1991, 1992) as well as the morphoclimatic reconstruction, based on the evolution of the clay minerals assemblages. The vertical evolution of both illite crystallinity index and illite/kaolinite ratio show an oscillating character allowing the establishment of the ritmicity and periodicity of the climatic episodes that have occurred in the region during the last centuries (Delgado *et al.*, 1994).

During the upper Cretaceous a major fault located immediately in the north of the Aveiro town unevenly the existing terrains. Along this fault the Rio Vouga fitted its terminal course. This fault quite possibly did conditioned later the erosion of the littoral area, particularly during the last sea retreat phase (Grimaldian) in which sea water level lowered 100 meters, approximately, as regards to the present day mean sea level (Teixeira & Zbyszewski, 1976).

The morphoclimatic evolution of the region had been studied, by several authors, particularly by Amorim Girão in 1941 (in Oliveira, 1988). This author produced several sketches, such as the one shown in Figure 3, that facilitated the understanding of the «Ria de Aveiro» evolution. In the sketch referred to, reference A represents the position of the Atlantic Ocean local margin during the stage in which the maximum advance of sea waters took place (c.a. 1000 years AC); reference B shows the coastline position in 1318 AC; reference C represents the present day position of the «Ria de Aveiro». Therefore, the present day sequential position of the different layers of mud, muddy sands, sands and gravels containing shell fragments reflect the lagoon evolution during historic times.

3. Materials and Methods

Lithological, sedimentological, mineralogical and geochronological studies were carried out on seven Holocene samples taken from four drilling cores (numbered 1 to 7) and also on three Cretaceous samples taken from outcrops (numbered Av 4 to 6). Samples were obtained either with rotation drilling and complete core recover or with an auger device. Only the samples extracted from rotation drilling cores were selected for dating, since samples derived from the auger device were somewhat disturbed.

Mineralogical studies were based mainly on X-ray diffraction (XRD) determinations, carried out in both the less than 63 μm and 2 μm fractions (clay fraction), and using methodologies referred to Rocha (1993). The <63 μm fractions were obtained through wet sieving with a 400 «mesh» sieve. For this separation distilled water has been used and the samples were mechanically dispersed with ultrasounds. Samples drying did take place in an oven at 60° C. Samples were removed from the oven before being fully dried; final drying did take place at room temperature. The <2 μm fraction (clay fraction) was obtained through sedimentation in accordance to Stokes law from a clay-distilled water suspension.

The clay mineral composition was determined both in oriented and non-oriented specimens. The oriented aggregates allow a preferential orientation of the platy crystals of the clay minerals enhancing the basal (001) reflections on X-ray diffraction patterns. In order to achieve that, clay fraction was deposited and dried at room temperature using a pipette and a thermically resistant (up to 600° C) glass slide.

For semiquantitative determinations of clay and non-clay minerals, criteria recommended by Schultz (1964) and Thorez (1976) had been followed. Areas under X-ray reflections characteristic of each identified clay mineral were measured; the measure areas were corrected taking into account the reflecting power of clay minerals.

Shells of *Cerastoderma sp.* were picked up in four levels of sandy muds and dated by the radiocarbon method. Radiocarbon datations were carried out in the «Laboratório de Isótopos Ambientais do Instituto

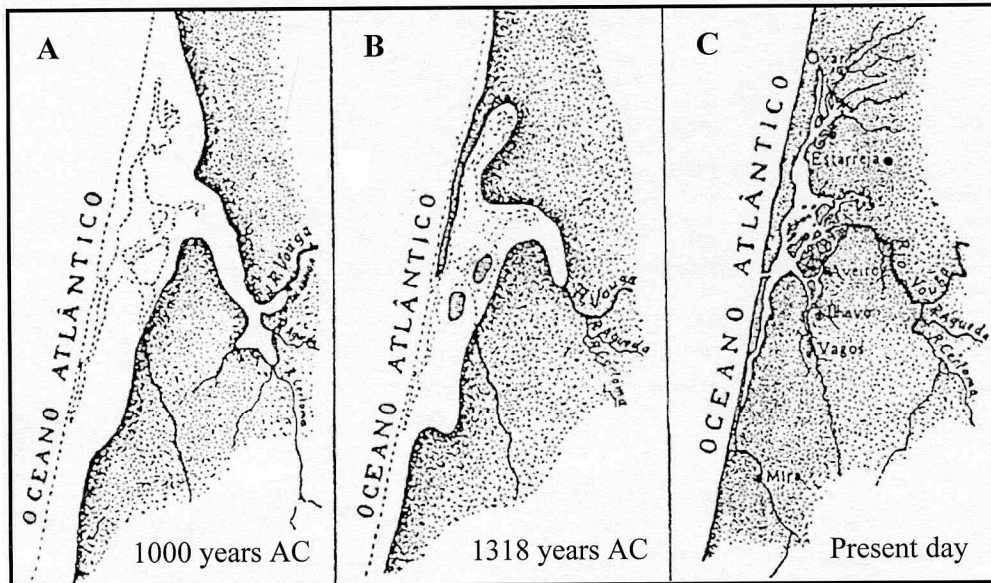


Figure 3. Historical evolution of the «Ria de Aveiro» (after Girão, 1941, in Oliveira, 1988)
 Evolución histórica de la «Ría de Aveiro» (Girão, 1941, en Oliveira, 1988)

Tecnológico Nuclear» (Sacavém, Lisboa), the data being corrected for the reservoir effect and calibrated according to Stuiver & Pearson (1993).

The geotechnical parameters analysed in this paper were taken from Galhano et al. (1997). Particular consideration was given to the expandibility test (according to the Portuguese LNEC E200-1967 norm), carried out on the less than 0.420 mm fraction, as well as to the Atterberg limits test (according to the Portuguese norm NP 143-1969), following the Casagrande test. Grain size distribution was assessed using an X-ray grain size analyser (Sedigraph).

4. Results and discussion

The surveyed mud levels are formed by dark grey sandy muds, silty muds and clayey muds, always very rich in Mica/Illite, sometimes with shells. Table 1 shows the mineral composition of the <math><63 \mu\text{m}</math> fraction (fine fraction) of the Holocene muds and Cretaceous clays and marls.

Quartz, Plagioclase and K-Feldspar are the other predominant minerals of the fine fraction (silt + clay), in general accompanied by Calcite (closely related with the shells) and discrete Dolomite. Gypsum, Anhydrite and other sulphates, Opal C/CT, Pyrite, Siderite and Marcassite are also common. Illite, Kaolinite, Smectite and discrete Vermiculite and Chlorite are the characteristic clay minerals of the <math><2 \mu\text{m}</math> fraction (clay fraction) of the Holocene muds and Cretaceous clays and marls, as shown in Table 2.

These mineral assemblages indicate lagoonal environments (Singer, 1984; Galán, 1986; Gomes, 1988; Chamley, 1989; Weaver, 1989; Rocha, 1996), under depositional conditions characterized by a relatively strong detrital supply, in a confined littoral area, with low salinity and anoxic conditions. The Illite abundance, characterized by a well ordered structure, indicates a temperate climate (Singer, 1984; Galán, 1986; Gomes, 1988; Chamley, 1989; Weaver, 1989; Rocha, 1996), with physical alteration prevailing over chemical alteration, but the Kaolinite contents indicates that the hydrolizing conditions due to rainfall and temperature were still important. The presence of Vermiculite, in the mud samples, reflect the nature of the recent sediments transported from the surrounding East region where a great variety of rocks do exist, such as: gneiss, micaschist, slate and sandstone.

Table 1. Mineral composition (in %) of the <63 μm fraction.
samples 1 to 7 - Holocene muds and clayey muds; Av samples - Cretaceous clays.

Composición mineralógica (%) de la fracción <63 μm .
Muestras 1 a 7 - lodos y lodos arcillosos del Holoceno; muestras Av - arcillas Cretácicas.

	1	3	4	5	6	7	Av-4	Av-5	Av-6
Quartz	30	27	27	28	30	35	8	10	9
Phyllosilicates	20	15	22	15	20	17	86	81	70
K-Feldspar	12	10	6	20	12	15	2	3	4
Plagioclase	12	20	10	13	18	7			2
Anhydrite	6	8	8	4	6	4	2	2	2
Opal C/CT	5	5	6	2	6	2			
Zeolites	2		4						
Pyrite	2	4	5	6		6			
Dolomite	2	3	4	5	2	10	2	2	13
Calcite	6	5	6	4	3				
Siderite	3	3	2	3	3	4		2	

Table 2. Mineral composition (in %) of the <2 μm fraction.

Samples 1 to 8 - Holocene muds and clayey muds; Av samples - Cretaceous clays.

Composición mineralógica (%) de la fracción <2 μm .
Muestras 1 a 8 - lodos y lodos arcillosos del Holoceno; muestras Av - arcillas Cretácicas.

	1	2	4	6	7	8	Av-4	Av-5	Av-6
Illite	70	60	67	68	60	58	73	74	77
Kaolinite	20	25	18	22	25	30	17	16	12
Smectite	4	7	7	4	6	5	10	10	11
Vermiculite	6	8	8	6	9	7			

On the other hand, these mineral assemblages allowed the mineralogical discrimination of the Holocene muds from the Cretaceous clays and marls, as shown in Table 3.

Table 4 shows the differential behaviour of the Holocene muds and the Cretaceous clays and marls in what concerns the geotechnical parameters.

The influence of textural, mineralogical and geochemical parameters on the geotechnical behaviour of the Cretaceous clays and Holocene muds of the Aveiro region has been studied by Galhano *et al.* (1997). The parameters referred to clays and muds belonging to these two formations were determined and correlated, using geostatistical analysis, with some relevant geotechnical parameters of the same samples. The data obtained allowed the subdivision of the region under study into distinctive sectors on the basis of the geotechnical behaviour. Clay fraction content and composition control geotechnical parameters, such as: expandability and the Atterberg plastic and liquid limits. A positive correlation was found between both expandability and Atterberg plasticity index values with total phyllosilicates, smectite, MgO and Al₂O₃ contents. However, Atterberg plasticity index values were relatively independent of the diverse clay mineral assemblages.

The first geochronological results obtained in the «Instituto Tecnológico Nuclear» (Lisboa), using the radiocarbon method were determined on bivalve shells collected in four sequential mud layers observed in the studied boreholes, yielded age values ranging in the interval 1960 \pm 90 and 6450 \pm 140 years BP, as shown in Table 5 (sample locations in Figure 2).

5. Conclusions

The mineral assemblages displayed by the Holocene muds of the Ria de Aveiro indicate lagoonal environments, under depositional conditions characterized by a strong detrital supply, in a confined, but low salinity, littoral area.

Table 3. Mineralogical discrimination of the Holocene muds from the Cretaceous clays and marls
Discriminación mineralógica entre lodos Holocenos y arcillas y margas Cretácicas

<i>Holocene muds</i>	<i>Cretaceous clays and marls</i>
Plagioclase	K-Feldspar
Calcite	Dolomite
Illite (ordered)	Illite (disordered)
Vermiculite	Smectite

Table 4. Geotechnical discrimination of the Holocene muds from the Cretaceous clays and marls
Discriminación geotécnica entre lodos Holocenos y arcillas y margas Cretácicas

<i>Geotechnical parameters</i>	<i>Holocene muds</i>	<i>Cretaceous clays and marls</i>
Expandability	Low expandability (10 to 20%)	Medium expandability (25 to 40%)
Plasticity	Very low plasticity (0 to 10%)	High plasticity (20 to 40%)
Clay fraction	Low contents (20 to 30 %)	High contents (60 to 80 %)

Table 5. Radiocarbon datation
Daticiones por Carbono 14

<i>Samples number</i>	<i>Laboratory reference</i>	<i>Corrected* datation</i>	<i>Calibrated** datation</i>
6	Sac-1476	2340 ± 80 years BP	1960 ± 90 years BP
2	Sac-1478	3340 ± 110 years BP	2960 ± 110 years BP
5	Sac-1477	4750 ± 140 years BP	4370 ± 140 years BP
4	Sac-1318	6830 ± 140 years BP	6450 ± 140 years BP

* Data corrected for the reservoir effect; ** Data calibrated according to Stuiver & Pearson (1993).

* *Datos corregidos para el efecto reservatorio*; ** *Datos calibrados de acuerdo con Stuiver & Pearson (1993)*

The first geochronological results (^{14}C) obtained in the «Instituto Tecnológico Nuclear» (Lisboa), determined on bivalve shells collected in four sequential mud layers, yielded age values ranging in the interval 1960 ± 90 and 6450 ± 140 BP. Samples 2 and 5, older than sample 6, belong to an unit that is incised on the unit of sample 6 (Figure 2). This indicates that samples 2 and 5 are reworked and located on the channel filling deposits.

On the other hand, these mineral assemblages allowed the mineralogical discrimination of the Holocene muds from the Cretaceous clays and marls. In general, the Holocene muds are richer in Plagioclase than in K-Feldspar, and also richer in Calcite than in Dolomite whereas in the case of the Cretaceous clays and marls it happens the reverse. In what concern the clay fractions, the Holocene muds present the assemblage Illite(ordered)-Kaolinite-Vermiculite whereas in the Cretaceous clays and marls the Illite(disordered)-Smectite-Kaolinite assemblage is predominant.

The analysed geotechnical parameters point out that the Holocene muds are less expansive and plastic than the Cretaceous clays and marls. Clays and marls are rich in clay particles whereas muds are rich in silt particles. The knowledge of the specific geotechnic characteristics of these two formations represents an effective tool for risk prevention and adequate for foundations planning of civil works to be set on the studied formations. To achieve this it would be convenient to take into account the information derived from the observations that could take place in the frequent excavations being carried out on the sands that overlie Cretaceous clays and marls and the Holocene muds as well. Excavation on clays and muds lead, frequently, to softening, expansion and retraction of the surface ground inducing undesirable collapses; the low load capacity of muds deserve a particular reference. In the case of the Forum de Aveiro a dual solution was adopted: 1) in the places where Cretaceous clays were easily reached, «footing» type foundations were based on clays; 2) where foundations on clays were economically unfeasible muds were replaced by «toutvenant».

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