Geological and geotechnical characterization of a Portuguese deposit of soft soils

Caractérisation géologique et géotechnique d'un depôt portugais de sols mous

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ABSTRACT: The soft deposit of Baixo Mondego has been the object of an intensive research programme devoted to its geological and geotechnical characterization. This paper presents the main geological features of the deposit and the most significant physical, identification, consolidation and stress-strain properties of the studied soft soils, obtained by different laboratory and in situ tests. The soils tested present several apparent inconsistencies, such as a great variability of the physical properties against their quite uniform composition, a very high plasticity that disagrees with the quantity and type of clayey minerals found and a quite unusual combination of high compressibility and high intrinsic resistance. Taking into account that the organic matter is responsible for all these original features of the soil's behaviour, it must be regarded as their most significant constituent, even if their organic content is relatively low.

RÉSUMÉ: Le depôt des sols mous de Baixo Mondego a fait l'objet d'un programme de recherche intensif consacré à sa caractérisation géologique et géotechnique. Cet article présente les principales caractéristiques géologiques du dépôt ainsi que les propriétés physiques, d'identification, de consolidation et de tension-déformation, les plus significatives des sols étudiés, qui ont été évaluées via différents essais réalisés au laboratoire et sur le terrain. Ces sols présentent plusieurs incohérences apparentes: la grande variabilité dés propriétés physiques s'oppose à la composition tout à fait uniforme, la plasticité très élevée est en désaccord avec la quantité et le type de mineraux argileux trouvés, enfin, la combinaison peu commune de compressibilité et de résistance intrinsèque toute deux élevées. Étant la matière organique responsable de toutes ces caractéristiques originales du comportement des sols étudiés, même si la teneur en matière organique est proportionnellement faible, celle-ci doit être considérée comme leur constituant le plus significatif.

1 INTRODUCTION

The soft deposit of Baixo Mondego, that covers the large alluvial plain of river Mondego, has been the object of a wide research programme developed at the Department of Civil Engineering of the University of Coimbra, primarily devoted to its geological and geotechnical characterization. This research programme has also embraced other related subjects, such as the observation and numerical modelling of some important embankments built on local soft soils, and will hopefully include the construction of a trial embankment. The geotechnical information herein presented was mainly obtained at the experimental site, though it agrees with the one deduced from different sites of the deposit.

This paper presents, for beyond the main geological features of the deposit, the most significant physical, identification, consolidation and stress-strain properties of the soft soils tested, as measured by the most popular laboratory and field tests. The soils from the deposit of Baixo Mondego have some unusual geotechnical characteristics, which result from the combined effects of their grain size, mineralogical and organic compositions. The organic matter is responsible for some of the apparently inexplicable features of the soil's behaviour, which are also found on other worldwide moderately organic soils. The understanding of organic soil's behaviour is still strongly encouraged by the progressive need to build on soft deposits, as a consequence of the lack of places presenting better geotechnical characteristics.

2 GEOLOGY OF THE DEPOSIT

Like many other similar alluvial deposits that exist in the world, the deposit of Baixo Mondego was formed under the geological conditions existing during and after the last glacial period, as a result of a sedimentary process that was strictly controlled by the sea level fluctuations occurring during the last 20,000 years. Because they are geologically so recent, these deposits do not generally present significant post-depositional effects.

2.1 *Formation*

During the peak of the last glacial period, the sea level was about 120 m below its actual position, as great amounts of water were required to form huge glaciers whose thickness could reach 2 or 4 km. As a consequence of the adjustment of the drainage system to those conditions, that strongly increased erosive action on the continent, especially at the rivers' mouth, deep valleys were formed along the rivers. Since that period, the progressive reduction of the glaciers' volume, resulting from significant climatic changes, induced a slow but sustained rise of the sea level up to present time. Many sedimentary deposits were then formed on the previously eroded valleys, as a result of the intensification of sedimentation caused by the reduction of the stream's speed. The increase of water's salinity near the sea and of organic substances in suspension, as biological life flourished, also contributed to the formation of large sedimentary organic deposits.

The deposit of Baixo Mondego was formed under the described mechanism, being river Mondego the agent responsible for the transportation of sediments resulting from the weathering of granite rocks found on upstream mountains. The deposit's mineralogical composition is determined by the sediments' origin, thus making quartz, micas and kaolinite the predominant minerals, while its grain size composition is controlled by the silt fraction, as a result of the sedimentary characteristics. The local presence of organic matter and fragments of shells from marine organisms is typical from the referred depositional environment.

2.2 *Post-depositional effects*

As in other geologically recent deposits, the post-depositional effects at the Baixo Mondego deposit are not highly expressive. Nevertheless, some few present significant importance, namely those resulting from the occurrence of desiccation, water table fluctuations or even secondary consolidation. As a consequence of the combined action of these phenomenons, a relatively stiff desiccated crust is commonly found at the deposit's surface and a light overconsolidation ratio can be expected in depth.

3 DEPOSIT'S GEOTECHNICAL CHARACTERISTICS

In order to determine the geotechnical properties of the deposit of Baixo Mondego, several in situ investigations were undertaken, particularly along the embankments of the IP3 main road section crossing the deposit and at the selected experimental site. Because of the quantity and quality of the information obtained at the experimental site, the results herein presented were generally obtained at this site, though they have been confirmed with other results from different sites of the deposit. The geotechnical information was measured by in situ and laboratory tests performed on both intact and reconstituted samples.

3.1 *Physical and identification properties*

The physical and identification properties of the deposit were established by tests performed in situ (water content and unit weight) and in the laboratory (identification properties and density of particles), or even by mathematical relations (void ratio and degree of saturation). The profiles of these properties are presented in Figure 1 for the local thickness of soft soils that reaches, in average, about 21 m.

The most significant features of the deposit's physical state, as Figure 1 shows, are the magnitude of some of its physical properties, from the water content to the unit weight, and also the highly expressive variability that nearly all the physical properties exhibit. In fact, the profiles determined prove that, except for the degree of saturation that is uniform in depth and very close to 100%, the physical properties of the deposit have an impressive variability, which is not a result of an inadequate tests' accuracy, since it was perceived with every alternative testing method used. The water content, for example, approximately ranges between 50 and 120 %, at a depth of 2 m. Besides from the important variability, the physical properties of the deposit also present quite unusual values, such as a water content that often exceeds 100 %, voids ratio as high as 3.1, a saturated unit weight that is rarely higher than 15 kN/m^3 and a density of the particles that, in average, clearly remains under 2.6.

The identification properties of the soft soils tested are also peculiar, especially when compared with the physical properties of the deposit and its mineralogical composition. The grain size composition of the deposit is relatively uniform (Fig. 1), being the silt the major fraction found. Clay is a minor fraction, usually not exceeding from 20 to 25 % of the soils' weight, and, as a result of the type of rock and weathering processes producing the sediments that formed the deposit, kaolinite is the unique clayey mineral found. The organic content of the deposit, measured by ignition loss at 400 °C and by wet oxidation using H_2O_2, is highly erratic. The values obtained by ignition loss, which proved to be more efficient, varied between extreme values of 3 and 13 %, though commonly presenting values from 5 to 10 %. The magnitude of the natural plasticity of the soils tested largely exceed, by every term used for comparison, what was expectable in face of the type and quantity of clayey minerals found. The most impressive values were obtained for the soils' activity that was evaluated between 1 and 4, thus presenting a magnitude hardly compatible with the activity of kaolinite ($\approx$ 0,4). This apparent inconsistency is determined by the presence of organic matter, which strongly increases soils' natural plasticity, as proven by the fact that the soils' plasticity strongly decayed with the progressive reduction of organic matter by ignition. Finally, it should be noted (Fig. 1) that, regardless of the depth considered, the soils' natural water content is generally close to or even higher than the liquid limit, demonstrating the deposit's softness.

The classification of the studied soils by the Unified System was established using the identification characteristics and considering that drying the soils at 100 °C reduced the liquid limit by more than 25 % (more than 50% at 400 °C). The soils were then classified as organic silts and clays of high plasticity, thus reflecting the influence of organic matter over soils' behaviour.

The tests performed and the analysis of the deposit's profiles of the physical and identification properties unequivocally prove the influence of organic matter over soils' properties, as observed on similar deposits by other authors (e.g. Amaryan 1993, Haan & Amir 1994, Hight et al. 1992). The organic matter strongly increases soils' properties variability, plasticity, water content and void ratio, and reduces their unit weight and particles density.

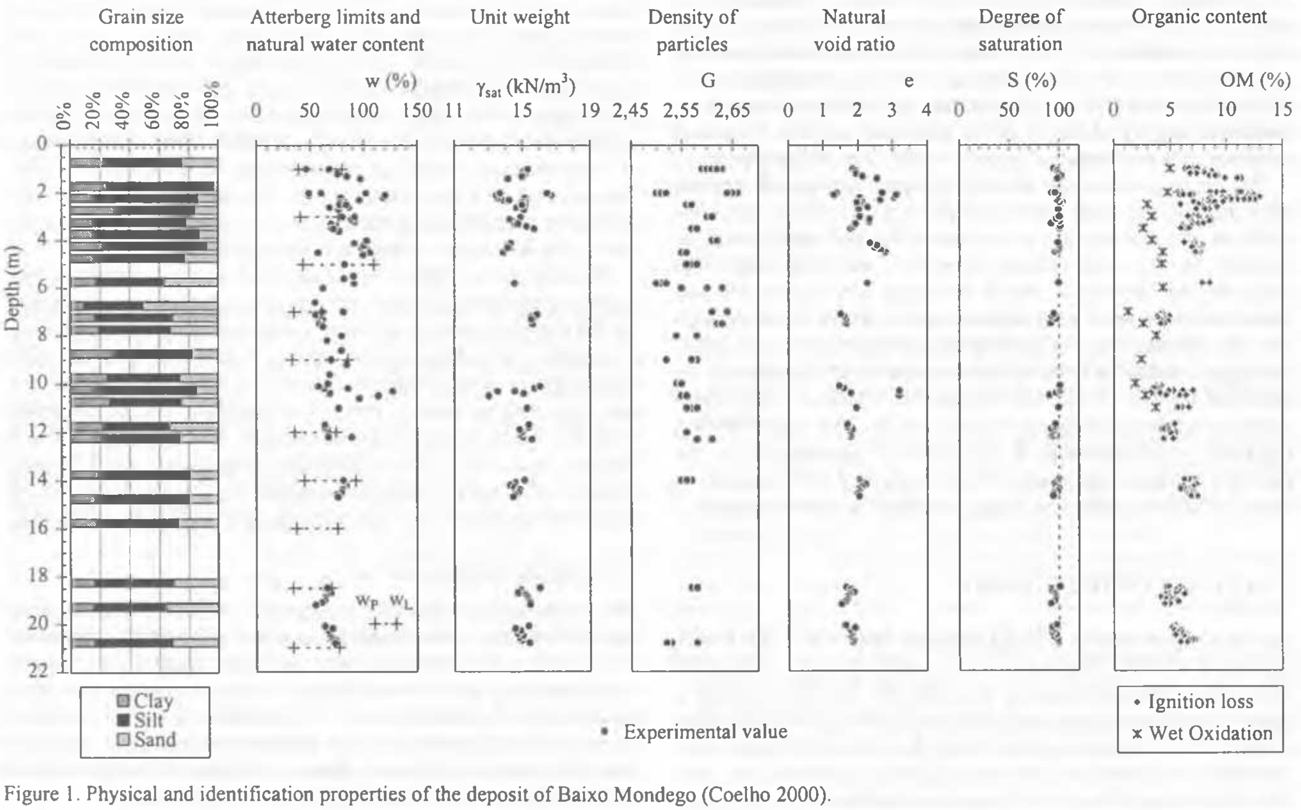

Figure 1. Physical and identification properties of the deposit of Baixo Mondego (Coelho 2000).

3.2 *Compressibility and consolidation properties*

The compressibility and consolidation properties of the deposit of Baixo Mondego, measured by oedometer tests performed on intact samples, are shown in Figure 2.

The first important conclusion is that the upper part of the deposit is overconsolidated, forming a desiccated crust with an OCR growing towards the surface. Below an approximate depth of 5 m, the deposit is normally consolidated or very lightly overconsolidated, contrarily to the expectations of a higher value of OCR resulting from secondary consolidation. It should be noticed that these results may be affected by the load imposed by a small embankment required by in situ investigation.

The parameters referring to the soils' intrinsic compressibility present values showing that the deposit is highly compressible. The most significant parameters determined, in regard to primary consolidation, are the compression index, C_c, varying between 0,41 and 1,24, and the ratio C_r/C_c, showing a mean value of 0,14. Even though the values found for the C_r/C_c ratio are quite normal, the magnitude of the values measured for C_c, usually exceeding 0.5, are uncommonly high and only acceptable in face of the soils' organic composition. The compressibility related to secondary consolidation is also characterized by parameters described by quite variable and relatively high values, although these are still consistently described by the Mesri's relation $C_\alpha/C_c = 0,05 \pm 0,01$, that the author considers to be typical of organic soils of high plasticity. The magnitude of the C_α/C_c ratio found at the deposit also adds to the initial supposition that the overconsolidation in depth should reflect more pronounced effects of the occurrence of secondary consolidation.

The vertical coefficient of permeability of the deposit was also evaluated using the results obtained from oedometer tests. k_v's values were found to approximately vary between 5×10^{-10} and 100×10^{-10} m/s, for the relevant in situ stresses. Although the values are typical of a soil containing clay, oedometer tests may not be the ideal way to evaluate soil's in situ permeability.

The experimental results obtained prove that the organic matter generally increases the soils' compressibility resulting from primary and secondary consolidation.

3.3 *Stress-strain-shear strength behaviour*

The stress-strain-shear strength behaviour of the studied soils was mainly determined by triaxial tests performed on intact and reconstituted samples. The laboratory undrained shear strength was then compared with the results of some in situ vane tests.

3.3.1 *Laboratory triaxial tests*

The laboratory testing programme aiming to establish the soils' stress-strain-shear strength behaviour included several series of triaxial tests, in every case using anisotropic consolidation. For intact samples, both the SHANSEP and Recompression to in situ stress methods were used. The shear was either produced by compression or extension, being average stress always increased.

One of the most significant results of the tests was the magnitude of the effective angle of shear resistance measured at the critical state, both in compression (37.8°) and extension (36.3°). Even though the values only reflect the analysis of reconstituted samples, they agree with the results obtained on intact samples, regardless of the reconsolidation method used. The intrinsic resistance seems determined only by the soils' granular fraction, and the fact that it looks incompatible with the soils' natural plasticity, which scantily depends on clayey minerals, is another mere consequence of organic matter's effects. In fact, if organic matter is removed, soils' plasticity matches intrinsic resistance.

The strains at failure showed values as high 7 %, in compression, and 14 %, in extension, which are in accordance with the previously observed high compressibility of the soils.

Figure 2 presents the deposit's profile of c_u/σ'_{v0} deduced from triaxial tests performed on intact and reconstituted samples, which again result in similar conclusions. Besides from the significant difference between the shear strength ratio obtained in compression and extension, it should also be noticed the high values found for c_u/σ'_{v0}, that for the normally consolidated soil ranges between 0.17 (extension) and 0.42 (compression). The variation of c_u/σ'_{v0} in depth reflects the local OCR's values.

These results prove that, because of organic matter, the soft soils tested exhibit a rather unusual combination of high intrinsic resistance with high natural plasticity and high compressibility.

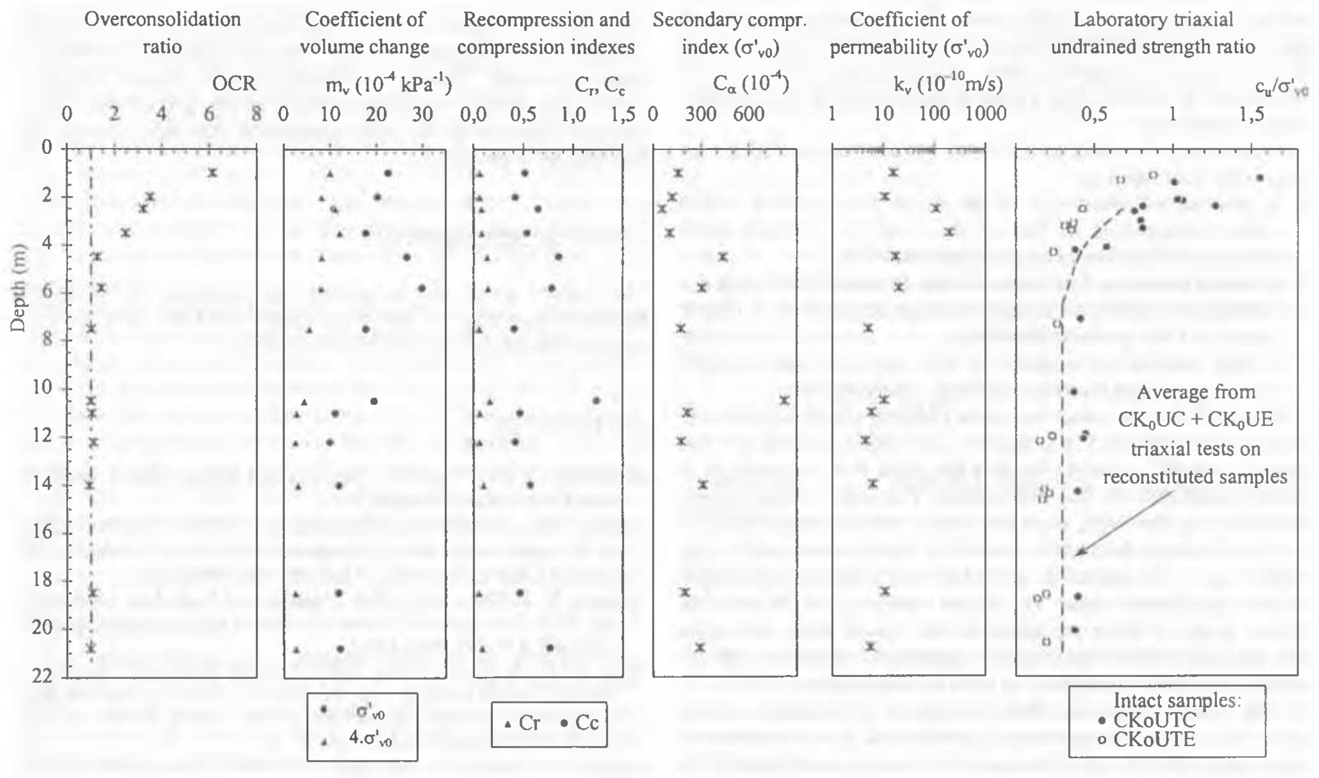

Figure 2. Compressibility, consolidation and undrained shear strength properties of the deposit of Baixo Mondego (Coelho 2000).

3.3.2 *Field vane tests*

Figure 3 exhibits the comparison between the undrained shear strength ratio measured by vane tests, in situ, and triaxial tests, in the laboratory. In order to produce a clearer figure, only the results of laboratory CK_0UTC and CK_0UTE tests performed on reconstituted samples are shown.

The results of the in situ vane tests qualitatively confirm the profile of the deposit's ratio c_u/σ'_{v0} deduced from triaxial tests, even if the ratio's values at similar depth usually present significant differences. At the heavily overconsolidated upper part of the deposit, in situ vane tests clearly predict an higher undrained shear strength ratio for the deposit than triaxial tests, once they provide values that generally exceed those resulting from CK_0UTC tests. This conclusion is sustained by the observations of Garga & Khan (1994), suggesting that the use of the vane test is particularly inadequate to evaluate the undrained shear strength of overconsolidated soils, namely at desiccated crusts, where, because of the increase of horizontal stresses resulting from the higher OCR, it tends to overestimate soils' resistance. On the contrary, at the highest deposit's depths, the vane tests results are close to those measured with CK_0UTE tests, thus implying a lower prediction for the soils global undrained strength. Taking into account that the company responsible for the execution of the tests reported difficulties when boring at higher depths, because of the inflow of water, the observed relation may be just an effect of the consequent soils' disturbance. In fact, considering the soils' characteristics at higher depths, namely their composition and overconsolidation ratio, there seems to be no other reason for the reduction of the undrained strength ratio measured by vane tests between the depths of 10 and 20 m.

Globally, the vane tests performed in situ do not seem to accurately predict the undrained strength ratio of the deposit, as problems apparently arise from their use either at the overconsolidated crust and at the bottom of the deposit.

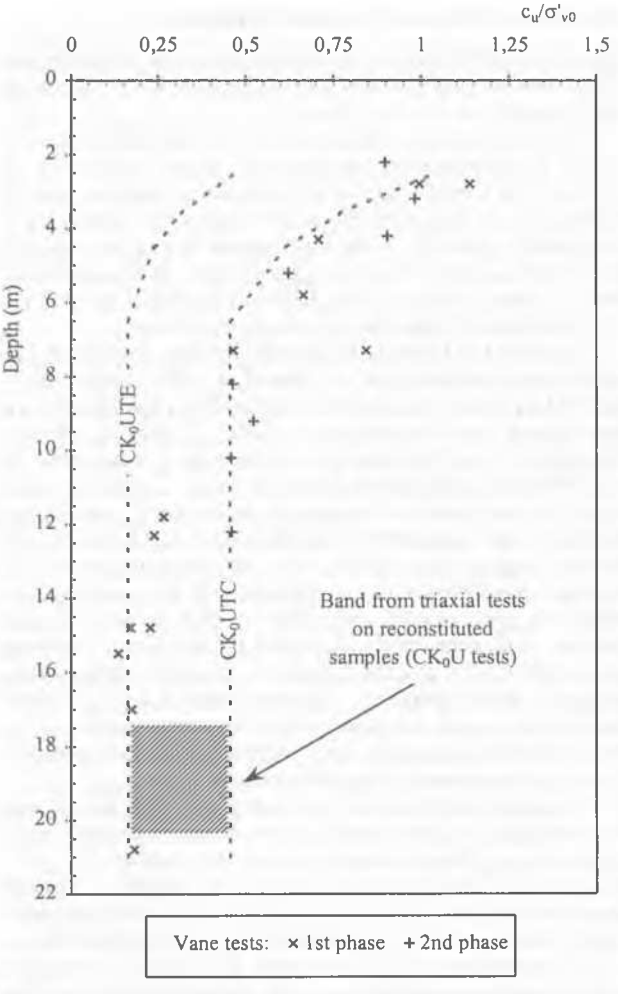

Figure 3. Comparison between undrained shear strength ratio measured by laboratory (triaxial) and field (vane) tests.

4 CONCLUSIONS

The soft deposit of Baixo Mondego is one of the worldwide sedimentary deposits formed after the last glacial period, as a result of the geological episodes and the sea level fluctuations occurring during the last 20,000 years. The deposit presents some quite unusual geotechnical characteristics that are mainly a result of the presence of organic matter, which, despite being a minor constituent of the soils, has a notable influence over almost every of their properties.

Apparently, the soils tested show several inconsistencies on their behaviour, such as:

1. a pronounced variability of the physical properties, which seems exaggerated in face of the relatively uniform grain size, mineralogical and organic compositions;
2. a natural plasticity that is much more expressive than was expectable on soils containing moderate amounts of a clayey mineral of low activity (kaolinite);
3. a quite unusual combination of high intrinsic shear strength with high natural plasticity and high compressibility.

It should also be noted that some physical properties, like the water content, the void ratio and the unit weight, possess unusual values, especially considering that the grain size composition is mainly controlled by the silt fraction. The soils' intrinsic compressibility is also high, since the values for the compression index was found to frequently exceed 0.5, being occasionally even higher than 1. As expected, secondary consolidation also exhibits very significant values. The values measured for the soils' effective angle of shear resistance at the critical state, averaging 37°, are compatible with the soils' granular composition, but extremely high when compared to their natural plasticity.

The results presented, that are typical from organic soils, show the strong influence that organic matter can have on soil's behaviour, even if, as in this case, it is a minor constituent. The results also make clear that the intrinsic resistance of these soils can not be correlated with their natural plasticity, using relations deduced from inorganic soils, where plasticity only depends on clayey minerals. Taking into account that the organic matter is responsible for the described features of the soil's behaviour, it must be regarded as the soils' constituent that most strongly influences their properties.

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