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Geotechnical properties of low density unsaturated carbonated clayey silts and impact on the foundation of canal embankments

Caractéristiques géotechniques de limons argileux carbonatés et non-saturés et leur impact sur la fondation des digues de canal

E.E. Alonso, E. Romero, D. Arnedo & S. Olivella
Department of Geotechnical Engineering and Geosciences. UPC. Barcelona, Spain

ABSTRACT
A carbonated collapsible silt in natural and compacted state has been tested. Parameters for an elastoplastic constitutive model (BBM) have been derived. Hydraulic properties were also determined. A simulation of canal embankments founded on these natural or compacted materials is then presented. The effect of rainfall and canal losses on the embankment performance is discussed.

RÉSUMÉ
Un limon effondrable et carbonaté a été étudié dans son état naturel et compacté. Les paramètres d'un modèle élastoplastique (BBM) ont été dérivés. Les propriétés hydrauliques ont de plus été déterminées. On présente la simulation d'une digue de canal construite sur ces sédiments naturels ou compactés. On discute l'effet de la pluie et des pertes en eau du canal sur la performance de la digue.

1 BACKGROUND

Extensive areas of the Ebro valley (Northeastern Spain) are covered by lightly cemented low-density clayey silts, which are prone to collapse upon wetting. Gypsum and carbonate cements are common. These low plasticity soils often fill wide depressions. They are frequently called "sediments of flat bottom valleys" because of the absence of established creeks. These soils have led to a number of failures and disorders in canals. A new canal has been planned and designed in Catalunya to bring Pyrenean water to the drier lands close to the Ebro river (canal Segarra-Garrigues). The canal will cross several "flat bottom valleys" where collapsible soils may reach 10 m of thickness. One of the procedures envisaged to avoid damage to the embankments, was to replace the natural low-density soil by the same material but compacted to a higher density. The geographical area is rather arid and with an annual mean rainfall in the range 400-500 mm. However, water losses from the canal may change this scenario dramatically.

This paper presents an study of the mechanical properties of the valley soils in its natural and compacted state. The objective of the tests performed in undisturbed blocks and compacted specimens was to develop constitutive models suitable for its use in a simulation of the performance of canal embankments. Some results of the simulation performed will be presented. Computer analysis were run with program CODE_BRIGHT (Olivella et al., 1996a, b), a general purpose finite element program for geotechnical analysis in saturated-unsaturated soils, developed at UPC. Hydraulic properties were also determined but they will not be reported here

2 MECHANICAL AND HYDRAULIC PROPERTIES

2.1 *Mechanical properties*

Identification properties of the natural soil, based on tests performed on several block samples recovered along the future canal, are given in Table 1.

Compaction of these soils reduces significantly their porosity. Void ratio at Optimum SP becomes half of the natural value.

Table 1. Range of geotechnical parameters of carbonated clayey silts. Segarra-Garrigues canal.

Water content (%)	Dry density (g/cm^3)	Void ratio	Liquid limit (%)	Plasticity index	Degree of saturation	Classification
10-22	1.25-1.60	0.70-1.05	24-38	7-13	0.35-0.65	CL-ML ML

Because of its simplicity and its capability to model most of the significant features of collapsible soils, the Barcelona Basic Model (BBM) (Alonso et al., 1990) was selected as a suitable constitutive model for simulations. In addition, only a few relatively simple tests are required to identify model parameters, which have been listed in the Appendix for convenient reference.

Wetting-under-load (collapse) tests were performed on natural and compacted specimens. If interpreted through BBM, they may provide some of the parameters listed in Appendix 1 (κ, $\lambda(o)$, β, r and p^c). One of the oedometer tests performed is shown in Figure 1. A large collapse was measured when the specimen was flooded under σ_v = 200 kPa. Once saturated, the compressibility coefficient, $\lambda(o)$, increases substantially. Collapse is plotted against the confining stress in Figure 2. The plot shows a common feature of low density unsaturated natural soils: they exhibit a maximum of collapse at some critical stress. Constitutive models, which reproduce this behavior, have been proposed by Balmaceda et al. (1992) and Alonso & Romero (2003). The simpler BBM predicts a continuous increase of collapse strain with confining stress. Given the actual height of most embankments of the Segarra-Garrigues canal (4-10 m) and the thickness of the natural deposits involved (4-10 m), in a significant proportion of cases, confining stresses will be smaller than the critical value identified in Figure 2 for a maximum of collapse. The selected parameters for BBM reproduce the increase in collapse strain with confining stress given in Figure 2 for confining stresses below the critical. In contrast, when these natural soils are compacted, collapse is almost eliminated, if densities are increased to the Standard (SP) or Modified (MP)Proctor optimum. This is also shown in Figure 2.

The virgin saturated compressibility of natural soils is very high (Fig. 3). Compaction is very effective reducing it, as shown also in the figure.

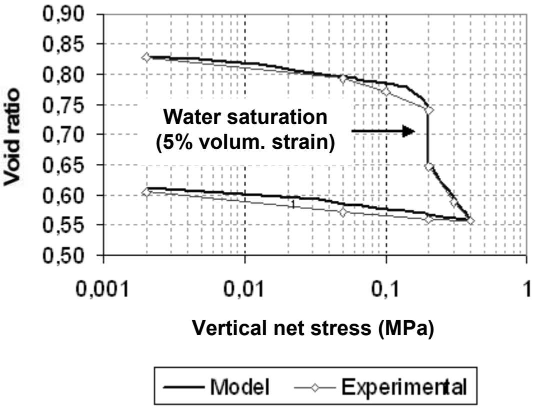

Figure 1. Collapse test on a natural soil from the Segarra-Garrigues canal.

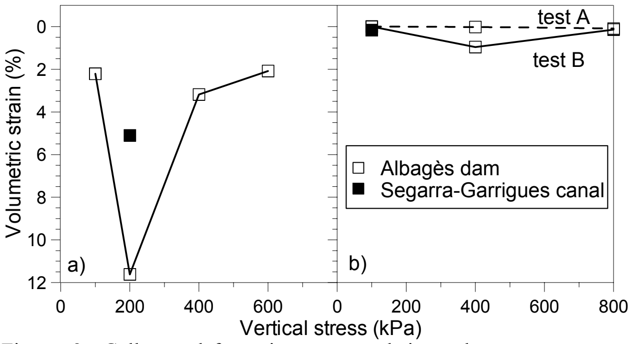

Figure 2. Collapse deformation measured in oedometer tests on a)natural and b)compacted specimens. Segarra-Garrigues and Albagés dam soils.

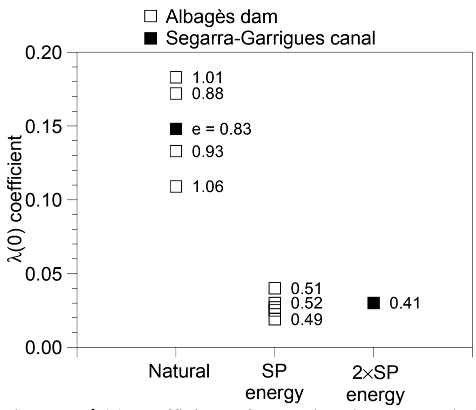

Figure 3. λ(o) coefficient of natural and compacted silt. Void ratio is also annotated.

Direct shear and triaxial CIU tests were also performed on saturated specimens of the natural and compacted soil. Figure 4a shows the results of two CIU tests performed on specimens of the natural soil previously saturated under a nominal confining stress. The path shows the initial elastic behaviour and the sudden transition into a micro-structural breakdown when positive pore water pressures are generated. In this occasion a zero cohesive intercept and an effective friction angle of 27.9º was measured. Friction angles in the range 27º-31º (and c' = 0) were measured in direct and triaxial shear tests. When compacted to optimum MP (Figure 4b) the soil becomes strongly dilatant and, measured friction angles increased to the range 34º-39º.

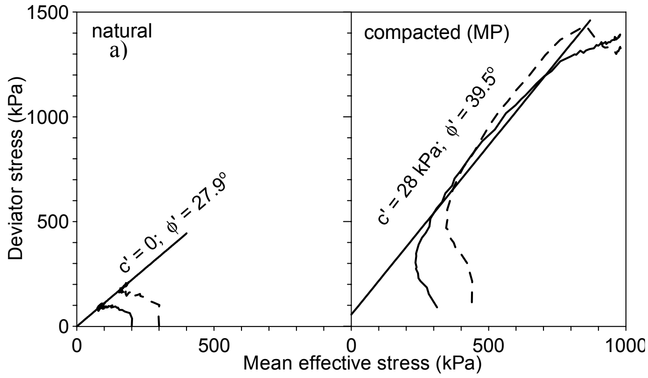

Figure 4. Triaxial CIU tests performed on specimens of natural and compacted silt.

An approximation of the "in situ" apparent preconsolidation stress was determined by means of isotropic compression tests performed on undisturbed (block) specimens. An example is shown in Figure 5 for two saturated specimens isotropically compressed to 200 and 300 kPa respectively. Radial and triaxial strain components were measured. The natural deposit exhibits some anisotropy (axial strains are larger than radial ones). A clear yielding of soil structure is observed for mean stresses close to 70 kPa. This data provides a direct estimation of p_o^*, the "in situ" saturated yield stress.

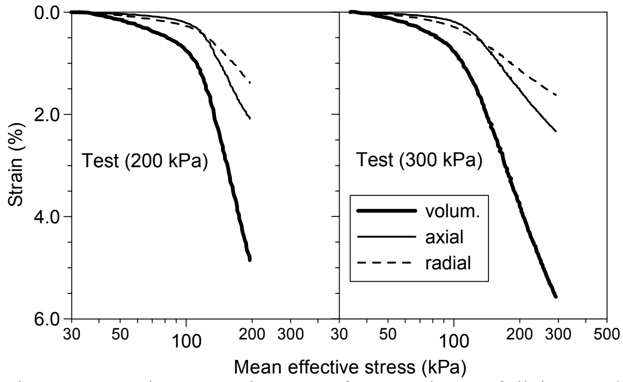

Figure 5. Isotropic compression stage of two specimens of silt in natural state.

Parameters for BBM were identified for the valley bottom silts for natural and compacted (SP optimum) conditions. They are collected in Table 2. A comparison of model response and oedometer test results for a specimen of natural silt is shown in Figure 1.

Table 2. Material parameters for natural and compacted valley silts. BBM model. Also shown are the parameters for the embankment material (a compacted argillite)(See Appendix for the list of parameters).

Parameter		Natural soil	Compacted soil	Embankment material
Elastic	κ	0.015	0.010	0.004
	κ_s	0.001	0.0005	0.001
	ν	0.35	0.3	0.35
Plastic volumetric compressibility	$\lambda(o)$	0.11	0.027	0.03
	β (MPa^{-1})	70	7.5	2
	r	0.7	0.8	0.8
Shear strength	k	0.004	0.05	0.06
	M	1.07	1.42	1.07
Reference stress	p^c (MPa)	0.01	0.01	0.01
Initial state	p_o^*	0.06	0.085	0.10
	s_i	0.1	0.5	0.1

3 PERFORMANCE OF CANAL EMBANKMENT

One of the representative embankments of the planned Segarra-Garrigues canal is shown in Figure 6. The embankment has a height of 10 m and the silt layer has a thickness of 7 m. No water table is present. The underlying strata, a hard Oligocene marl-sandstone sequence is assumed to be rigid. The purpose of the analysis is to know the canal performance under different hypothesis of rain distribution and intensity of water losses. The canal lining was simulated by a porous elastic slab. All the remaining materials are described by the BBM model .

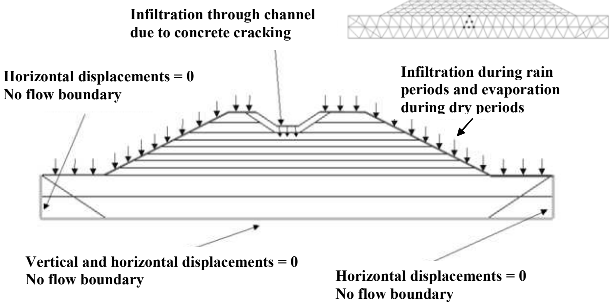

Figure 6. Canal embankment founded on a layer of collapsible natural silts and quadratic triangular elements of the FE discretization.

Among the alternatives considered to improve the foundation soil, the solution of soil excavation and replacement by the excavated material once compacted was also examined. The embankment was to be built with compacted Oligocene marls. This material was also tested and model parameters were identified, although details are not given here. The set of material parameters used in simulations is given in Table 2.

A periodic rainfall infiltration record was applied to the surface of the model. The basecase was a monthly-based yearly record measured on a village in the vicinity of the canal project. It corresponds to the year 1997. The total rainfall this year was 423 mm, close to the average of the last 25 years (430 mm). A constant relative humidity (60%) was assumed to apply at the boundary, when no rain is present. The yearly record of 1977 was repeated, every year, in the simulations performed. Rainfall was supposed to act at the end of the construction period. The embankment construction was simulated by the successive accumulation of layers during a short period (30 days). Impervious boundaries were assumed during embankment construction. Once built, the canal lining was assumed to receive a constant head. Water loses of different intensity may be simulated by modifying the lining permeability.

Consider first the case of the embankment founded on the natural silts and an "impervious" canal lining. Figures 7, 8 and 9 show the settlement response, pore-water pressure records and stress paths (s, p plane) of some representative points. The "dry" month (February) dominates the evolution of pore water pressures, which, in the long-term remain negative in the foundation and in the embankment. The initial construction loading results in plastic volumetric compression, as the LC yield curve is displaced. This stage corresponds to the initial calculated settlement. Later, suction changes remain essentially within an elastic region and no irreversible accumulation of settlements are calculated.

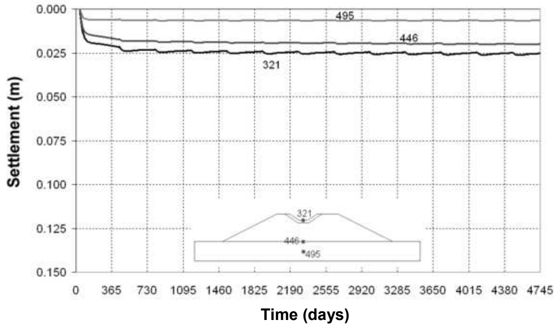

Figure 7. Evolution of settlements of some points due to embankment construction and rainfall action. Embankment founded on natural soils.

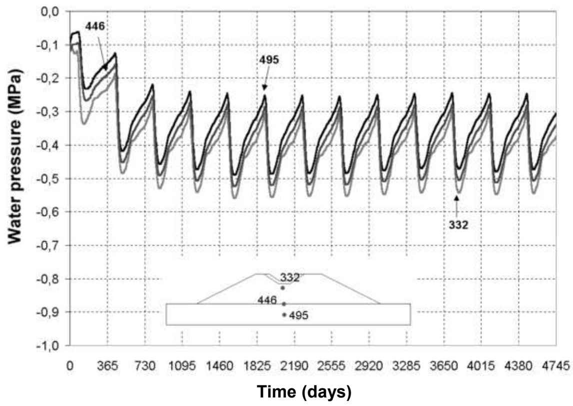

Figure 8. Evolution of pore water pressures of some points due to embankment construction and rainfall action. Embankment founded on natural soils.

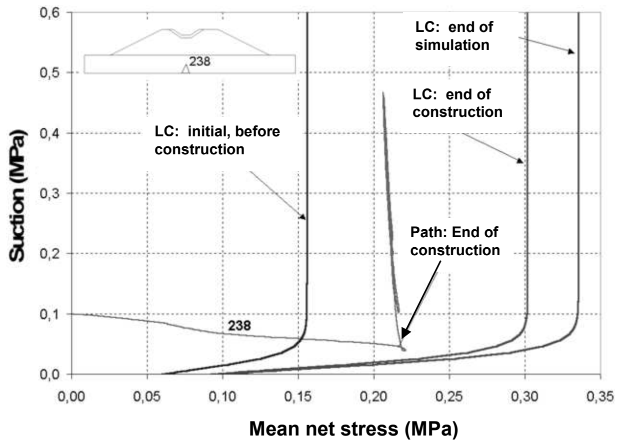

Figure 9. Stress paths of some points during embankment construction and rainfall action. Embankment founded on natural soils.

Consider, however, a different scenario: water is lost through insufficiently sealed joints of the lining. This situation is simulated by an increased lining permeability. Moderate and heavy losses are simulated by means of lining permeabilities equal to 8 $\times$ 10^{-8} and 8 $\times$ 10^{-7} m/s. If this change takes place at day 1000 after the beginning of the simulation, the structure reacts as shown in Figure 10, in terms of computed settlements. The moderate loss results in a progressive accumulation of settlement, which is accelerated during the first few years after the initiation of the leakage (heavy losses). Again, the settlement rates are accelerated during the wet months. The continuous supply of water is now able to offset the beneficial effect of the dry month. The structure seems to reach now a steady state situation, which has mobilized the full collapse potential of the foundation silts. Note that computed settlements are large and capable of major destruction. Since the occurrence of significant leakage is a likely situation, the foundation soils had to be improved. The effect of replacing them by compacted soils is shown in Figure 11 for the same scenario (heavy water losses in this case). The bottom foundation slab experiences some movements, but their magnitude is small. Note also that periodic (elastic) swelling-settlement movements are calculated. "Swelling" is associated now with periodic positive increments of pore water pressure, which result in a reduction of effective stresses.

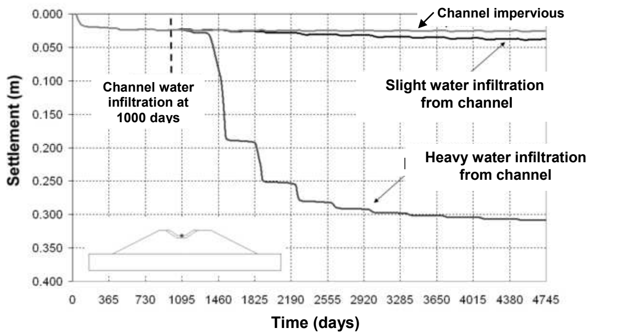

Figure 10. Evolution of settlements of some points due to embankment construction, rainfall action and canal leakage (slight water losses). Embankment founded on natural soil.

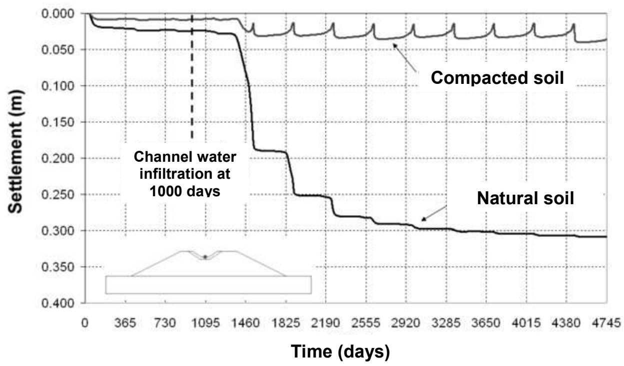

Figure 11. Evolution of settlements of some points due to embankment construction, rainfall action and canal leakage (heavy water losses). Embankment founded on natural soil.

4 CONCLUSIONS

The paper describes the behavior of natural carbonated low plasticity and low density silts and clayey silts, which fill often valleys of arid regions of the Ebro river valley, in North-East Spain. Their collapse potential is a permanent threat to infrastructures and, in particular to irrigation canals. Mechanical properties are also given for the same material, compacted to SP optimum. In both cases, a simple elastoplastic BBM model may reproduce the most significant features of behavior of these unsaturated materials. Model parameters have been derived from a few conventional laboratory tests performed on undisturbed block specimens (for the natural soil) and on compacted specimens. Hydraulic properties (permeability and water retention) were also experimentally determined but have not been reported here. This identification work was part of the design process of a large irrigation canal crossing these natural deposits. A fully coupled hydro-mechanical computer code for unsaturated-saturated soils was then used to simulate the performance of canal embankments under different scenarios. Only a few details of the analysis are presented here. Average rainfall-evaporation conditions were defined on the basis of existing meteorological records. Leakage losses out of the canal were also introduced in the analysis. It was found that canal settlements could be moderate even if the natural foundation soils are not improved. This is due to the arid nature of the average climatic record. However, the risk is high and heavy rains or canal leakage may lead to a dramatic acceleration of movements associated with silt collapse. The compacted silt is stable enough to react with very limited movements under extreme environmental conditions. The case illustrates the capabilities of current hydro-mechanical computer models, coupled with elastoplastic formulations of unsaturated soil response, to perform realistic analyses of geotechnical structures under realistic environmental actions.

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APPENDIX. PARAMETERS OF BBM

Elastic behaviour

- κ: Elastic volumetric compressibility
- κ_s: Elastic compressibility against suction changes
- G: Shear modulus

Elastoplastic volumetric compressibility

- $\lambda(0)$: Slope of saturated virgin compression line
- β, r: Provide the change of the unsaturated compression coefficient as suction changes

Strength

- M: Slope of critical state line
- k: Rate of increase of apparent cohesion with suction