Self-weight collapse of Loessic Soils. Prediction by simple models
(Autocolapso de Suelos Loessicos. Modelos Sencillos de Predicción)

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2011 Pan-Am CGS Geotechnical Conference

ABSTRACT
Córdoba city has several kinds of loessic soils, with differences in the settlements due to the collapse of the internal structure during wetting. Most of these soils require external load for collapsing, but approximately 15% of the area contains self-subsiding soils type. When these soils are loaded with any construction, problem gets worse. There are laboratory and field tests for characterizing these behaviors. Settlement patterns in buildings have been evaluated using full scale prototypes, with different types of foundations in the 1970s. The ground was wetted through septic wells and loose connections pipes. Settlement measurements were followed for over two years. Recently, some schools buildings have been founded in collapsible soils. One of them has a deep septic well whose infiltration caused a localized increase in the groundwater level, leading a deep collapse around it. The settlements were propagated to the surface, creating a crater that reached the outbuildings. For the purposes of this research, there were made surface leveling and drilling in the influence area. The interpretation of the pattern of settlement produced by the advance of saturation was done with a simple model. There are comparison with this real case and prototype testing.

RÉSUMEN
La ciudad de Córdoba presenta distintos tipos de suelos loessicos, con diferencias en los asentamientos debido al colapso de la estructura interna, cuando el suelo se humedece La mayoría de estos suelos requieren de carga externa para que el fenómeno se produzca y aproximadamente, en el 15% del área, son autocolapsables bajo su propio peso. Cuando estos suelos están cargados por alguna construcción, el problema se agudiza considerablemente. Para estudiar estos comportamientos y tipificarlos, existen ensayos específicos tanto de laboratorio como in-situ. Las características del asentamiento en las construcciones han sido evaluadas mediante prototipos a escala natural, con distintos tipos de fundaciones, en la década de 1970. Se hizo colapsar al suelo mediante la pérdida de un pozo absorbente y sus conexiones y se midieron deformaciones durante más de dos años. Recientemente, se han construido en Córdoba algunas escuelas que se fundaron en suelos autocolapsables. En el caso particular de este trabajo, se presentan los estudios realizados en una de ellas, en donde un pozo de infiltración profundo generó un aumento localizado del nivel freático produciendo el colapso en profundidad. Los asentamientos se propagaron a la superficie, generando un cráter que alcanzó a las construcciones aledañas. A los fines del estudio, se efectuaron nivelaciones en superficie y perforaciones en la zona de influencia. Para la interpretación se empleo el modelo de asentamientos producido por el avance de la saturación. Se comparan los resultados entre el caso real y los ensayos de prototipos previamente descriptos.

1. INTRODUCTION

Silty soils with metastable structure (due to the increase of moisture content), occupy the central semiarid region of Argentina, particularly in Córdoba city.

These metastable soils may suffer the collapse of their internal structure under the action of its own weight, without increment of external forces (Terzariol, 2010) when wetted (self weight collapsing soils).

There are different kinds of loessial soil, showing differences in the settlements due to the collapse of the internal structure when the ground is wet. Most of these soils require external load in order to the phenomenon occurs, but approximately 15% of the area are occupied by selfcollapsing soils, (Rocca et al. 2006). To study these behaviors, and typify this kind of soils, there are specific tests both laboratory (Rocca et al. 1992) and in-situ (Terzariol et al 1999).

A previous research in the National University of Córdoba, that includes test on prototypes allows analyze those results against the behavior of buildings in this research, where there are similarities and differences.

The geotechnical background of the city, plotted in collapsibility maps indicate that the area has a potential settlement of about 45 cm., in case of saturation of the first twelve meters.

During the years 1999 and 2001, in the west suburbs of Cordoba, it was built a school complex that consists of a kindergarten, a primary school and a high school.

The geotechnical exploration carried before the construction shows a thickness larger than 30 meters of silty self-weight collpasing soils.

The structures consists in precast reinforced concrete columns, beams and panels, simply supported each one or connetced mean welded steel plates. The structures are founded by frictional auger and cast in place piles, 15,00 meters deep.

The sewage, after being treated, are dumped in the ground through a 30,00 meters deep well. The drainage well (yellow point), was located in proximity to a sports courtyard. Figure 1 shows the facilities.

Figure 1. View of School`s Buildings. Source: Terzariol, 2009.

During years 2007 and 2008 it began to appreciate movements in building structures due to differential settlement, with widening of construction joints and damage to some service nets (like gas and water). This situation led to the closure of kindergarten and the implementation of a geotechnical and structural assessment.

A set of field actions, like land and geotehcnical surveys, were performed. Based on the characterization of the soil profile, and its comparison with the situation prior to the wetting process, enough data was available in order to use a numerical model for estimate settlements produced by front saturation advance (Terzariol et. Al. 2003; Zeballos et al., 2007). This model allows comparisons between field results and those obtained in the simulation, validating the explanation of the phenomena represented.

2. PREVIOUS TESTS ON PROTOTYPES.

In the 1970´s, in situ tests were performed on prototype housing located in the Campus of the University of Córdoba (Moll and Reginatto, 1972).

The soil involved was loessial sandy and clayey silt with self-weight collapsible characteristic.

Five of it were built with different types of foundation and a field´s long-term wetting. Each prototype has water reservoirs, connected to a system of pipes with construction defects, that converged to a central infiltration well. Like it can be see in the figure 2.

After 100 days it can be saw the presence of a crater concentric with the well.

The test was performed during more than 2 years and measures of settlements were done periodically. The results of measured settlement against time are plotted in figure 3.

There are curves that represent each one of the 5 differents types of foundation, like spread foundation, different deep of piles, and so on.

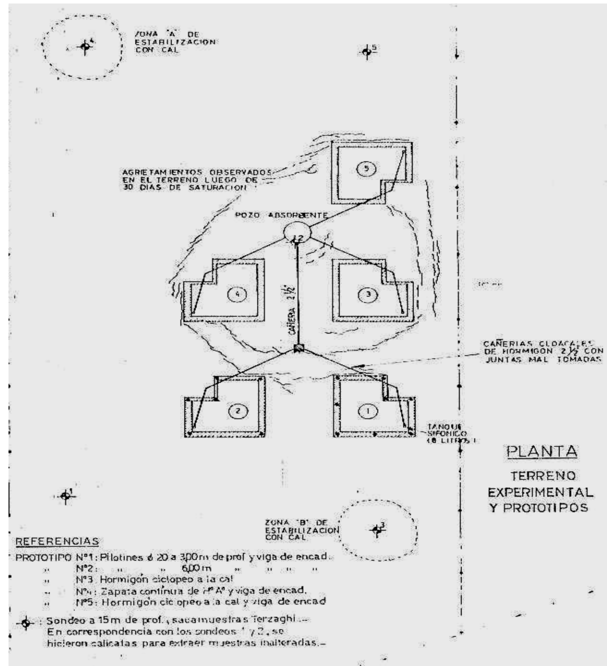

Figure 2. Plan of Prototypes and crater contour. Source: Moll, 1972.

In these tests the water income from the surface from the open joints between sections of pipes, and lesser extent from infiltration well.

Nevertheless the crater is approximately concentric with the infiltration well.

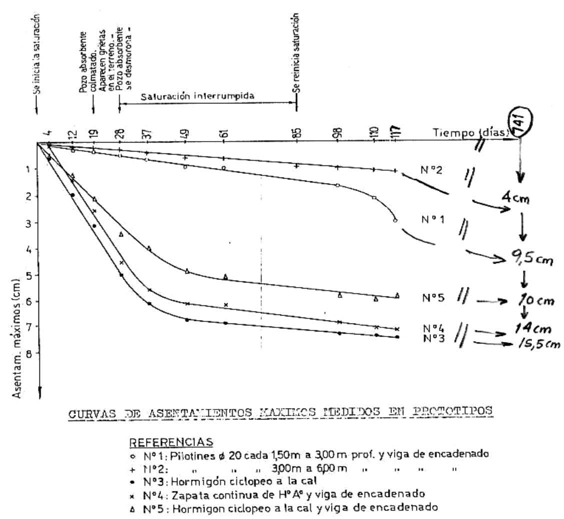

Figure 3. Settlement against time. Source: Moll, 1972.

The maximun measured settlement in prototypes after 2 years was 0,16 meters (Rocca, 2005).

3. CHARACTERIZATION OF SOIL PROFILE.

In the school complex, it was performed two SPT tests with sampling and a surface survey of the entire area.

The maximum distortion between prefabricated panels in kindergarten, were about 10,00 cm with total settlements on the same order.

This led to movements between beams and columns, breaking some welded joints. In the other buildings it could be seen that these settlements showed a smaller distortion. The settlements converged on the center of the area, which was evidenced by joint movements. In the courtyard was found an accumulation of rainwater near a little wall located close the sewage drainage.

The land survey confirmed the findings of the initial inspection, as shown in Figure 4. The maximum relative settlement, between the perimeter and the center, of the area in the order of 40 to 50 cm. Contours of settlements shows a remarkably symmetrical subsidence around the source of income water.

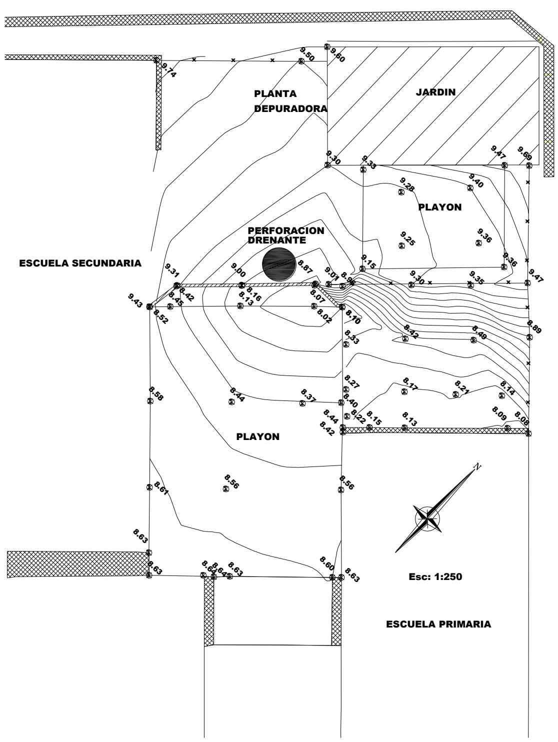

Figure 4. Land survey after subsidence. Souce: Terzariol, 2009.

These magnitude and contours of settlements was similars to those wich were found in previous research, (Moll and Reginatto, cited above). In both cases generated a concentric depression, but the infiltration in the University Campus trial was an infiltration from the surface, while the schools were from lower to up. Differences in measured strains are about 2.5 times higher in present research due to the thickness of soil involved and relative collapsibility in each case.

Two boreholes, S1 and S2 were performed. S1 close to the drainage well, and the other (S2), off the area, about 30,00 meters north of the first survey.

In both cases the soil was silty loessial selfcollpasing soils. For this kind of soil is common to find a void ratio (e) close to 1, with specific gravities (Gs) of approximately 2.7 and dry unit weight of 12 to 13 kPa. With these values, a mositure content between 27% and 32%, mean degree of saturation (S) close to 100%. The current moisture content found in the samples taking fron the boreholes are higher than those detected in the geotechnical exploration conducted prior to construction. In turn, the moisture values recorded in the survey near the drill drainage show values close to saturation at depths below those detected in the probe located outside.

3. BEAHVIOR MODELIZATION

Prediction of volumetric change associated with collapsible soils can be estimated through the use of stress-strain models. In these problems, soil properties are usually nonlinear. However, some cases can be treated using parameterized models of linear increase, or solved through the use of elastoplastic models. In the case of collapsible soils, the volumetric change is commonly associated with changes in soil suction and broken cemented links.

It is necessary to combine both seepage and stress analysis, coupled or uncoupled, to solve the problem (Fredlund, 2006).

These stress-strain models have varying degrees of complexity. Their use is recommended on the basis of general stress paths in each problem. The relative collapse model (Redolfi, 1990), is an alternative simplified analysis of the problem, used particularly in cases where the soil undergoes continued increases in moisture content. For situations in which stress paths show more complexity, for example developing variations of moisture in alternative processes of wetting and drying, there are applicable elastoplastic constitutive models, as proposed by Alonso et al. (1990).

The method of relative collapse, is based on the identification of a "function of collapse." This function associates the settlements observed in the soil as a result of increases in external pressure applied and the soil moisture content. In this sense, allows the construction of a surface state in the space of total stress (σ), moisture (w) and settlement or collapse (δ). This collapse can be expressed as:

$$\delta_i = \alpha(w) \cdot (\sigma_{i,f} - \sigma_{i,o})^{\beta(w)}$$

Where δi is the collapse occurred on the "i" element of the geotechnical profile, divided in "n" elements, σ_{io} and σ_{if}, are the initial and final stresses in the "i" element, α (w) and β (w) are functions dependent on soil moisture content.

Finally, the total settlement is the summation along the soil profile of the individuals settlements in each element (Mustafaev and Sadetova, 1983; Redolfi, 1990). The total settlement (Δ) produced in the geotechnical profile is calculated as:

$$\Delta = \sum_{i=1}^{n} \Delta_i = \sum_{i=1}^{n} \delta_i \cdot H_i$$

where "Δi" is the settlement occurred in the element "i", and "Hi" is the thickness of the layer.

The parameters involved in the calculation of settlement are obtained in laboratory tests. In these research it have

taken, as reference, the results of confined compression tests performed on undisturbed samples of silt clay and sandy loam loessic (Aiassa et al., 2008).
The initial moisture condition was identified, and it has been considered as a reference moisture content for the purpose of the assessment of settlements sustained by the sample to similar conditions of external pressure and higher humidity values. The initial moisture content was 16.0%, obtaining the relative vertical deformation curve (ε) depending on the applied external stress. The difference between these strains and the obtained for other moisture content defines the relative collapse between the initial state and it that corresponds to a moisture content condition considered in each case.
The results show a nonlinear relationship between variables involved. Based on these responses is possible to identify two distinct sectors. A first sector, with exponential growth on the collapse. This condition is maintained constantly up to value of external pressure from which the collapses are held constant, or tends to produce a slight decrease. For the first sector, it can be identified α and β, for a mean external pressure of 100 kPa. The results, together with the application of model are depicted in Figure 5.

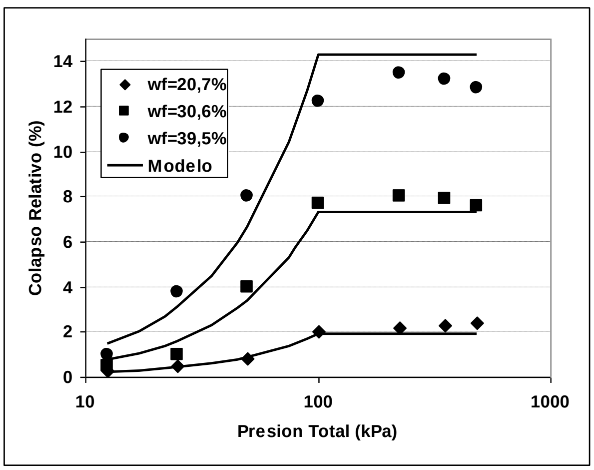

Figure 5. Experimental results of studies on collapse and relative collapse model. Source: Aiassa, 2008

The parameter "β" is slightly constant and equal to 1.10. The parameter α has been linked to changes in moisture content. The quadratic relationship are the following:

$$\alpha = 7{,}31x10^{-5} \cdot \Delta w^2 + 2{,}10x10^{-3} \cdot \Delta w$$

4. ANALYSIS CONDUCTED

The modeling involved the evaluation of settlements expected as result from the change in the moisture content of the soil profile. It was considered two different moisture states.
The initial stage has been characterized by values obtained before the construction, and the final stage through the results of the tests carried out after settlement.

For the development of numerical analysis have been implemented following assumptions:

• The observed settlements are produced as a result of modify the moisture content, between the initial and final stage.
• The settlement involved an area large enough to be considered dominant one-dimensional phenomenon. Consequently, the effects generated by shear stress, are neglected.
• The relative collapse equation has a maximum value of settlement for states applied vertical pressure equal to 100 kPa. For values above assumes that produces a similar response to that obtained for the value above.

The steps followed in the modeling were as follows:

• Identification of the moisture content and the initial total pressures.
• Moisture content observed in the boreholes S1 and S2. In each one are estimated, so the new total pressure value acting as amended by the variation of moisture, as the actual increase in moisture content. According to this increase, in relation to the reference humidity, the coefficient α is evaluated at each level of implementation of the profile considered.

Moisture states considered in the initial condition and in the final state in the two positions shown are presented in Figure 6.

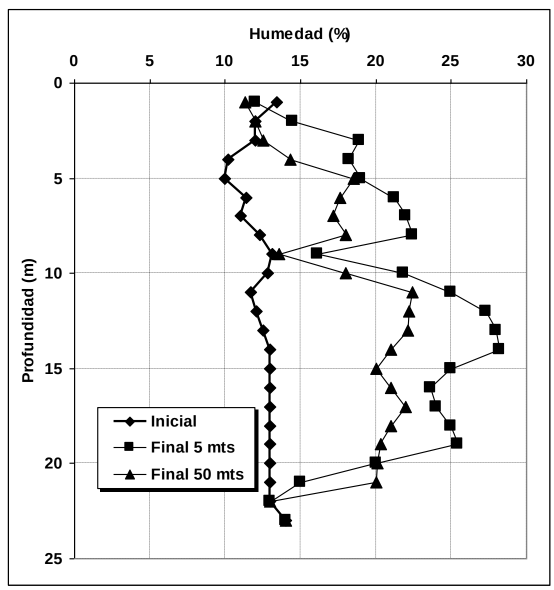

Figure 6. Moisture content profile at initial and final stages

• The collapse is based on the total external pressure acting on each level of profile and change depending on the moisture content. These collapses are transformed in settlements, and then integrated for the whole profile considered. Figure 7 shows the cumulative settlement from the point of greatest depth in the profile to the surface. Total settlements are close to 0.50 meters near the well. The relative settlements between these point and the points were the boreholes were performed are 0,25 meters.

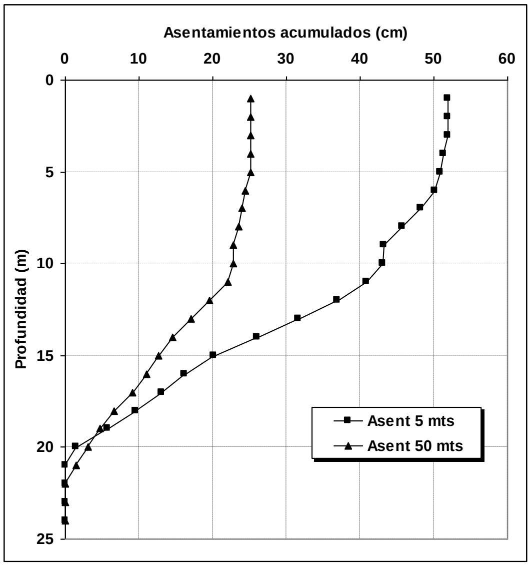

Figure 7. Total settlement estimated at final stage.

5. CONCLUSIONS

• The water infiltrated from the drainage well produces the saturation of soil layers with the consequent settlement and nearby structures.
• The settlement of the collapsible soil layer dragged floating deep foundations.
• The increase of the moisture content, confirm the above assumptions.
• Soil collapse originated the general subsidence with peaks near the sewage well.
• There are a good consistency between the values measured in field and the numerical modeling results.
• It has been similar performances, between the test carried out during the 70´s in the University Campus, and the observed settlementes in the present research, although in this case the saturation was caused by rising water table.
• The relative collapse model used, despite its simplicity, requires the definition of a set of calibration parameters, which may be changed if soil conditions are alterated. However, its simplicity allows calibrations in order to consider the soil changes, based on classic papers.
• The model used has an important application when the increase of saturation degree and external pressures are evidents. For stress paths more complex the model has limitations, and it can be used elastoplastic matric suction.
• The use of such models can be a very important tool for the general characterization of collapsible soil areas and allows mapping of risk.

ACKNOWLEDGEMENTS
Research supported by Science and Technic Secretary - National University of Córdoba and Ministry of Science and Technology - Government of Córdoba, Argentina.

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